International Hydrogen Ramp-up Program – H2Uppp

Green Hydrogen for Energy Self-Sufficient Hotels, Resorts and Islands

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Terms and Definitions

Term	Definition
AEM	Anion Exchange Membrane Electrolyzer
AFC	Alkaline Fuel Cell
ALK	Alkaline Electrolyzer
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BESS	Battery Energy Storage System
BOQ	Bill of Quantities
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
EMS	Energy Management System
EPW	EnergyPlus Weather
EUI	Energy Use Intensity
HESS	Hydrogen Energy Storage System
iDPP	Integrated development partnership with the private sector
LCC	Life Cycle Costs
LCOE	Levelized Cost of Energy
MCFC	Molten Carbon Fuel Cell
NPV	Net Present Value
NMBE	Normalized Mean Bias Error
PEM	Proton Exchange Membrane Electrolyzer
PAFC	Phosphoric Acid Fuel Cell
PCS	Power Conversion System
PEMFC	Proton Exchange Membrane Fuel Cell
PV	Photovoltaic
RFP	Request for Proposal
SOEC	Solid Oxide Electrolyzer Cell
SOFC	Solid Oxide Fuel Cell
TGO	Thailand Greenhouse Gas Management Organization

Executive Summary

Southeast Asia is home to approximately 30,000 islands, of which an estimated 8,000 to 9,000 are inhabited. A significant share of these islands lacks connection to the mainland electricity grid and relies primarily on diesel generators for power supply. Hotels and resorts are often the main electricity consumers on such islands, particularly in countries where tourism plays a central economic role, such as Thailand. While diesel-based power generation provides reliability, it is associated with high operating costs, greenhouse gas emissions, local air pollution, noise exposure, and environmental risks related to fuel transport and storage. Against this background, the decarbonisation of off-grid islands represents both a challenge and an opportunity for sustainable development in Southeast Asia.

Within the framework of the International Hydrogen Ramp-up Programme (H2Uppp), this project assessed the technical and economic feasibility of green hydrogen as part of an energy self-sufficient, carbon-neutral energy supply system for hotels, resorts, and small islands. The project was implemented as an integrated development partnership with the private sector (iDPP) and focused on a real-world pilot site: Koh Munnork (Rayong), a privately owned island resort in the Gulf of Thailand that is currently supplied exclusively by diesel generators.

The project was structured into five work packages. Following the identification of suitable pilot locations, Koh Munnork was selected due to its off-grid status, high occupancy rates, and strong interest from the resort operator. A comprehensive market study then assessed hydrogen technologies and suppliers available in Southeast Asia, with particular attention to robustness, maintenance requirements, and applicability in remote island environments. Proton Exchange Membrane (PEM) fuel cells and Anion Exchange Membrane (AEM) electrolyzers were identified as the most suitable technologies for the considered scale and operational conditions.

The core of the project was a detailed feasibility study analysing the existing energy supply system, electricity demand, and environmental impacts at Koh Munnork. The study revealed that the resort consumed approximately 266 MWh of electricity per year and emitted nearly 290 tonnes of CO_2 annually due to diesel use. In addition to greenhouse gas emissions, the current system causes significant local impacts, including noise levels exceeding occupational safety thresholds for staff, risks of diesel and lubricant spills, and exposure to harmful exhaust emissions.

Based on measured load profiles and occupancy data, a carbon-neutral, energy self-sufficient supply concept was developed, consisting of a photovoltaic (PV) system, a battery energy storage system (BESS) for short-term storage, and a hydrogen energy storage system (HESS) comprising an electrolyzer, hydrogen storage tanks, and a fuel cell for long-term storage. An Excel-based simulation and optimisation tool was developed to size and economically optimise the system components.

Several system configurations were evaluated and compared to a diesel-only baseline. The analysis showed that a hybrid system combining PV, batteries, and a moderately sized hydrogen system represents the economically optimal solution. While investment costs for renewable and hydrogen-based systems are significantly higher than for diesel generators, the life-cycle cost analysis demonstrated that the optimised PV/HESS/BESS configuration achieves lower life-cycle costs and a lower levelized cost of energy (LCOE) than continued diesel operation. The hydrogen system primarily serves as a long-term storage and backup solution, ensuring energy security during extended periods of low solar radiation.

During the assessment of the technical feasibility of the Koh Munnork pilot project particular attention was given to site selection, logistics, and system integration under challenging island conditions, including limited accessibility, transport constraints, and environmental exposure. Containerised system components and dedicated transport solutions enabled feasible installation despite the absence of port infrastructure. In parallel, permitting requirements involving multiple governmental authorities were identified early, underlining the importance of proactive coordination to ensure smooth implementation. Overall, the technical concept and implementation approach provided a robust and replicable model for renewable, hydrogen-based energy systems in remote island and resort applications.

The study further identified financing as a critical barrier to implementation. Although Thai commercial banks offer green loan products, interest rates remain relatively high and reductions for green projects are marginal. Moreover, the Koh Munnork project faces additional challenges due to the lack of land ownership by the resort operator, which prevents the use of the site as loan collateral. As a result, conventional bank financing is considered unlikely. In contrast, government-backed development banks and international programmes offering soft loans or grants were identified as promising alternatives to reduce upfront investment barriers and improve project bankability.

To assess transferability, a parameter study was conducted for selected locations in Indonesia, the Philippines, and Vietnam. The results indicate that climatic differences within Southeast Asia have only a minor impact on electricity demand for resort applications. While system sizing requires moderate adjustments, the overall system architecture remains valid across all assessed locations. Economic feasibility is driven primarily by local diesel prices rather than climate, with particularly strong potential in countries with high fuel costs or difficult fuel logistics.

Finally, project results were disseminated through three regional events, including hospitality and green hydrogen conferences, reaching stakeholders from the tourism sector, technology providers, financial institutions, and policy organisations. These activities contributed to knowledge transfer, increased awareness of hydrogen-based off-grid solutions, and supported dialogue on replication and scale-up.

In conclusion, the Koh Munnork project demonstrates that green hydrogen-based hybrid energy systems can provide a technically robust and economically viable pathway to decarbonising off-grid islands and resorts in Southeast Asia. While upfront investment and financing challenges remain, the project provides valuable evidence, design methodologies, and lessons learned to support future replication under the H2Uppp framework and beyond.

1 Introduction

1.1 Background information

It is estimated that out of the approximately 25,000[1] islands in Southeast Asia around 8,000[2] islands are inhabited, see Figure 1. Of these islands several thousand are supplied by isolated power systems rather than mainland grids. They have either no electricity at all or are supplied by diesel generators or hybrid systems consisting of photovoltaic and diesel generators. In some cases, main energy consumers on these islands are hotels and resorts since the hospitality sector plays a major role in Southeast Asia in general and in Thailand in particular.

Figure 1. Southeast Asia with approximately 25,000 islands (Source: Google Maps)

Indonesia:	~17,000–17,500 islands
Philippines:	7,641 islands
Malaysia:	878 islands
Thailand:	~1,430 islands
Vietnam:	~3,000 islands

All countries in Southeast Asia have signed the Paris Agreement, committing to ambitious climate targets. Consequently, the decarbonization of off-grid islands will be a key challenge in the coming years. It can be foreseen that carbon-free energy supply systems consisting of photovoltaic and adequate energy storage systems such as green hydrogen and batteries will play an important role bridging the energy supply during nighttime or days with low solar radiation.

Also, these systems can help electrifying islands and remote areas which are populated but have no access to electricity at all. In such contexts, electrification is not merely a technical infrastructure challenge but a fundamental enabler of socio-economic development. Access to reliable and affordable electricity is a prerequisite for basic public services such as lighting, drinking-water supply, healthcare, education, and telecommunications. For many remote islands in Southeast Asia, the absence of grid connection has historically limited economic opportunities, constrained living standards, and reinforced geographic isolation. Electrification therefore directly contributes to poverty reduction, improved resilience, and inclusive development, in line with the Sustainable Development Goals.

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[1] R.W. Shaw & P. H. B. F. de Jong (eds.), *The Physical Geography of Southeast Asia*, Oxford University Press / Springer reference series.

[2] Indonesia has around 6,000 inhabited islands (ADB, 2016; BPS/BIG), and the Philippines about 2,000 (Philippine Statistics Authority).

1.2 Project goals

The idea of this iDPP (integrated development partnership with the private sector) is to investigate the potential and use of green hydrogen as energy storage in hotels, resorts, and small islands without grid connection. Off-grid hotels, resorts and islands usually depend on diesel generators. To provide a potentially cheaper and more sustainable option, energy storages in combination with solar energy would support the decarbonization of remote areas, improve grid stability and reduce the negative impact of diesel generators on the immediate surroundings (noise emissions, exhaust gas emissions, oil spills).

The following technologies are compared:

- Diesel generator (conventional solution)
- BESS (off grid: PV & batteries)
- HESS (off grid: PV & batteries & H2 system (electrolyzer, H2 tank, fuel cell))

The three energy supply technologies will be holistically compared on the example of Koh Munnork Private Island in Thailand regarding the following aspects:

- Global environmental impact (carbon emissions, global warming)
- Local environmental impact (oil spills, noise and exhaust emissions)
- Investment costs
- Operation and maintenance costs
- Payback time
- Life cycle costs

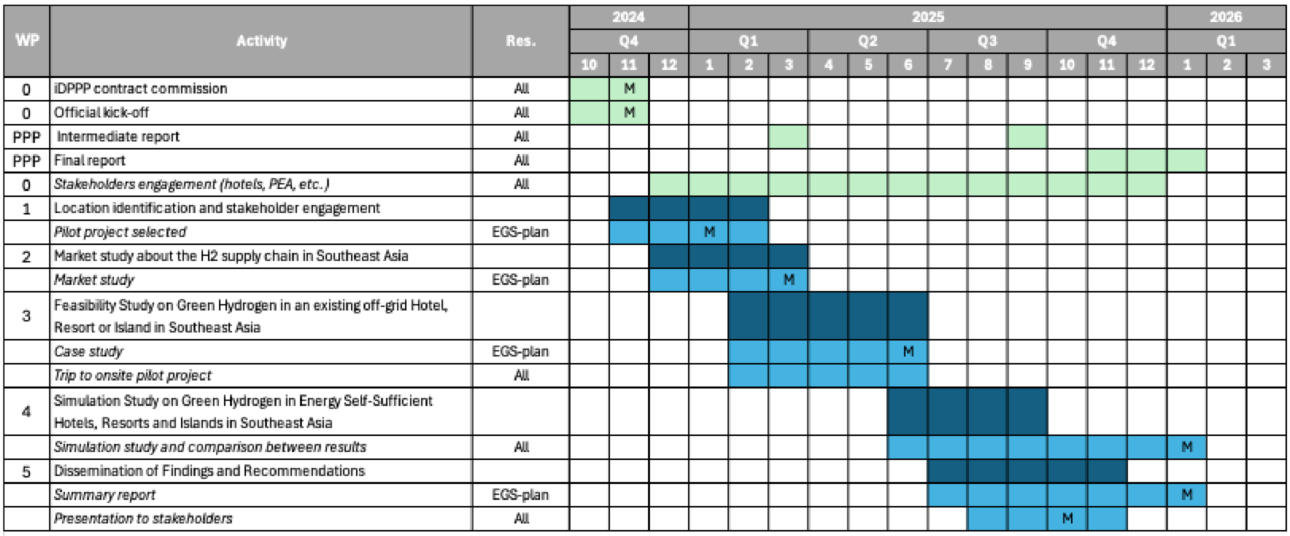
1.3 Project implementation

The following five work packages were defined to implement the project:

WP1: Location identification and stakeholder engagement
WP2: Market study about the H2 supply chain in Southeast Asia
WP3: Feasibility Study on Green Hydrogen in an existing off-grid Hotel, Resort or Island in Southeast Asia
WP4: Parameter Study on Green Hydrogen in Energy Self-Sufficient Hotels, Resorts and Islands in Southeast Asia. The parameter study assesses the impact of the location within Southeast on the system capacity and economic feasibility.
WP5: Dissemination of Findings and Recommendations

The timeline of the project is September 2024 to February 2026, see Table 1. The timeline table illustrates the phased implementation of the hydrogen project from Q4 2024 to Q1 2026 and reflects the structured progression from project initiation to completion.

Table 1. Project timeline (Source: EGS-plan (Bangkok) Co., Ltd.)



WP	Activity	Res.	2024			2025												2026		
			Q4			Q1			Q2			Q3			Q4			Q1		
			10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
0	iDPPP contract commission	All	🟩	🟩 M																
0	Official kick-off	All	🟩	🟩 M																
PPP	Intermediate report	All						🟩						🟩						
PPP	Final report	All														🟩	🟩	🟩		
0	*Stakeholders engagement (hotels, PEA, etc.)*	All			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩			
1	Location identification and stakeholder engagement			■	■	■	■													
	Pilot project selected	EGS-plan		🟦	🟦	🟦 M	🟦													
2	Market study about the H2 supply chain in Southeast Asia				■	■	■	■												
	Market study	EGS-plan			🟦	🟦	🟦	🟦 M												
3	Feasibility Study on Green Hydrogen in an existing off-grid Hotel, Resort or Island in Southeast Asia						■	■	■	■	■									
	Case study	EGS-plan					🟦	🟦	🟦	🟦	🟦 M									
	Trip to onsite pilot project	All					🟦	🟦	🟦	🟦	🟦									
4	Simulation Study on Green Hydrogen in Energy Self-Sufficient Hotels, Resorts and Islands in Southeast Asia										■	■	■	■						
	Simulation study and comparison between results	All									🟦	🟦	🟦	🟦	🟦	🟦	🟦	M		
5	Dissemination of Findings and Recommendations											■	■	■	■	■				
	Summary report	EGS-plan										🟦	🟦	🟦	🟦	🟦	🟦	M		
	Presentation to stakeholders	All											🟦	🟦	🟦 M	🟦				

The project commenced in late 2024 with preparatory activities. This initial phase focused on project setup, stakeholder engagement, and the definition of core assumptions and boundary conditions. Early coordination ensured alignment among project partners and established a solid foundation for the subsequent technical and organizational work.

The main development phase took place throughout 2025. During the first half of the year, a market and technology study, system design, and feasibility assessments were conducted. Several activities were implemented in parallel to optimize the overall timeline and to enable iterative refinement of results.

In mid to late 2025, the project transitioned toward refining the feasibility study, conducting the simulation study and starting with dissemination.

The final phase in early 2026 focused on consolidation, writing the summary report and project closure. Remaining activities comprised final validation, documentation, and handover of results.

2 Work Package 1: Project Identification

2.1 Selection criteria

The core of the project is a feasibility study based on an existing hotel or resort in Southeast Asia (WP3). Therefore, the first work package focuses on the identification and selection of a suitable pilot project. The following criteria should be fulfilled:

- Hotel / resort or small island without connection to the public grid of the respective mainland
- Location in Southeast Asia.
- High occupancy (utilization) rate throughout the year to ensure sufficient operating hours and make the carbon-neutral concept economically feasible.
- No environmental or regulatory constraints.
- Good data availability.
- On-site technician for technical support.
- Willingness by the owner to participate.

2.2 Potential locations in Thailand

Most islands in Thailand are grid-connected to the mainland. Based on the selection criteria the following islands in Thailand without grid-connection and with hotels / resorts were identified, see Figure 2.

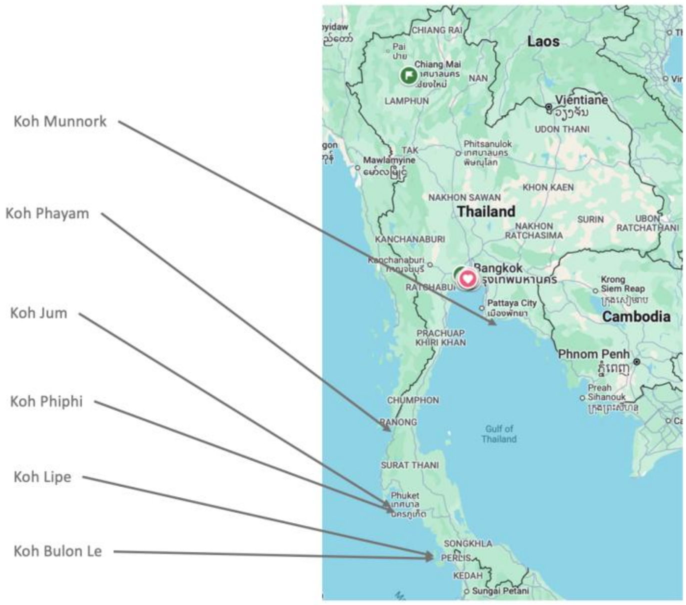


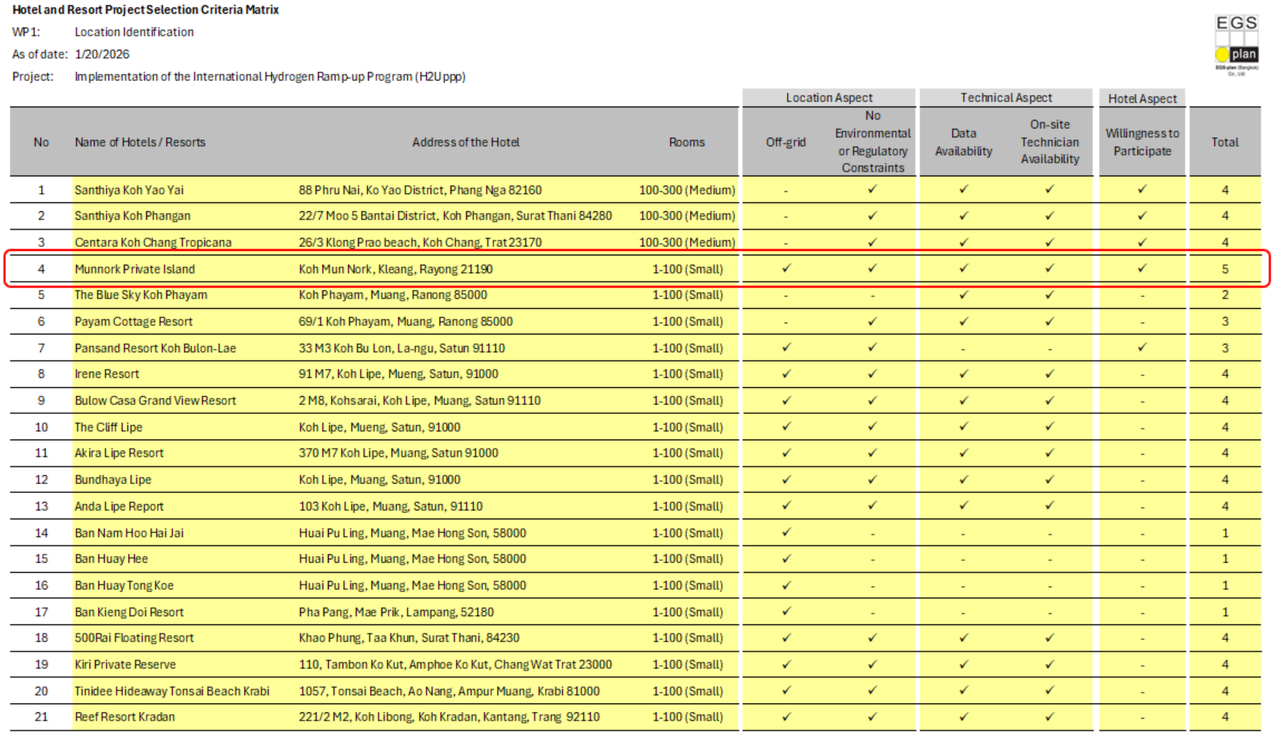
Figure 2. Off-grid islands (not exhaustive) with hotels and resorts (Source: EGS-plan (Bangkok) Co., Ltd. based on Google Maps)

2.3 Project identification

The islands of Koh Lipe and Koh Payam in Thailand were pre-selected due to the high quantities of hotels and resorts. However, during the assessment it was found that hotels and resorts on Koh Payam are located in areas which are subject to environmental and regulatory restrictions, including mangrove areas. Therefore, Koh Phayam was excluded from the long list.

Due to the high number of hotels in Koh Lipe a list of hotels with high room rates was created by using Google Maps. It can be assumed, that hotels with high room rates like luxury hotels and resorts have more financial possibilities to implement such a project in future. The hotels were subsequently called by telephone, and interviews were conducted with the hotel managers. Important criteria were requested and compiled in an overview table to support the selection process, see Table 2. The most important criteria were location (off/on grid, environmental or regulatory constraints, data availability, onsite technicians and willingness to participate).

Table 2. Hotel longlist (Source: EGS-plan (Bangkok) Co., Ltd.)



Hotel and Resort Project Selection Criteria Matrix
WP1: Location Identification
As of date: 1/20/2026
Project: Implementation of the International Hydrogen Ramp-up Program (H2Uppp)

				Location Aspect		Technical Aspect		Hotel Aspect	
No	Name of Hotels / Resorts	Address of the Hotel	Rooms	Off-grid	No Environmental or Regulatory Constraints	Data Availability	On-site Technician Availability	Willingness to Participate	Total
1	Santhiya Koh Yao Yai	88 Phru Nai, Ko Yao District, Phang Nga 82160	100-300 (Medium)	-	✓	✓	✓	✓	4
2	Santhiya Koh Phangan	22/7 Moo 5 Bantai District, Koh Phangan, Surat Thani 84280	100-300 (Medium)	-	✓	✓	✓	✓	4
3	Centara Koh Chang Tropicana	26/3 Klong Prao beach, Koh Chang, Trat 23170	100-300 (Medium)	-	✓	✓	✓	✓	4
4	Munnork Private Island	Koh Mun Nork, Kleang, Rayong 21190	1-100 (Small)	✓	✓	✓	✓	✓	5
5	The Blue Sky Koh Phayam	Koh Phayam, Muang, Ranong 85000	1-100 (Small)	-	-	✓	✓	-	2
6	Payam Cottage Resort	69/1 Koh Phayam, Muang, Ranong 85000	1-100 (Small)	-	✓	✓	✓	-	3
7	Pansand Resort Koh Bulon-Lae	33 M3 Koh Bu Lon, La-ngu, Satun 91110	1-100 (Small)	✓	✓	-	-	✓	3
8	Irene Resort	91 M7, Koh Lipe, Mueng, Satun, 91000	1-100 (Small)	✓	✓	✓	✓	-	4
9	Bulow Casa Grand View Resort	2 M8, Kohsarai, Koh Lipe, Muang, Satun 91110	1-100 (Small)	✓	✓	✓	✓	-	4
10	The Cliff Lipe	Koh Lipe, Mueng, Satun, 91000	1-100 (Small)	✓	✓	✓	✓	-	4
11	Akira Lipe Resort	370 M7 Koh Lipe, Muang, Satun 91000	1-100 (Small)	✓	✓	✓	✓	-	4
12	Bundhaya Lipe	Koh Lipe, Muang, Satun, 91000	1-100 (Small)	✓	✓	✓	✓	-	4
13	Anda Lipe Report	103 Koh Lipe, Muang, Satun, 91110	1-100 (Small)	✓	✓	✓	✓	-	4
14	Ban Nam Hoo Hai Jai	Huai Pu Ling, Muang, Mae Hong Son, 58000	1-100 (Small)	✓	-	-	-	-	1
15	Ban Huay Hee	Huai Pu Ling, Muang, Mae Hong Son, 58000	1-100 (Small)	✓	-	-	-	-	1
16	Ban Huay Tong Koe	Huai Pu Ling, Muang, Mae Hong Son, 58000	1-100 (Small)	✓	-	-	-	-	1
17	Ban Kieng Doi Resort	Pha Pang, Mae Prik, Lampang, 52180	1-100 (Small)	✓	-	-	-	-	1
18	500Rai Floating Resort	Khao Phung, Taa Khun, Surat Thani, 84230	1-100 (Small)	✓	✓	✓	✓	-	4
19	Kiri Private Reserve	110, Tambon Ko Kut, Amphoe Ko Kut, Chang Wat Trat 23000	1-100 (Small)	✓	✓	✓	✓	-	4
20	Tinidee Hideaway Tonsai Beach Krabi	1057, Tonsai Beach, Ao Nang, Ampur Muang, Krabi 81000	1-100 (Small)	✓	✓	✓	✓	-	4
21	Reef Resort Kradan	221/2 M2, Koh Libong, Koh Kradan, Kantang, Trang 92110	1-100 (Small)	✓	✓	✓	✓	-	4

Beside Koh Lipe, a resort located on Koh Munnork / gulf of Thailand became aware of the iDPP project and expressed interest in participating. On 28 November, the resort manager attended the official project kick-off ceremony held at the German Embassy in Bangkok. Subsequently, a detailed introductory meeting with the resort management took place on 29 November at the EGS-plan office in Bangkok, during which the project objectives and initial information about the resort were exchanged.

Based on these discussions, it became evident that the Koh Munnork resort fulfilled all criteria for serving as a pilot project for an energy self-sufficient and carbon-neutral resort. Consequently, a Memorandum of Understanding (MoU) was signed between the resort and EGS-plan on 13 December, marking the formal commencement of the project.

3 Work Package 2: Market Study

3.1 Goals of the market study

The goal of the market study is to get an overview of hydrogen technologies and different suppliers with a focus on the applicability on islands and in remote areas in Southeast Asia. Especially the following aspects were assessed:

- Investment costs
- Maintenance and repair
- Robustness (water quality, salty air)
- Availability in Southeast Asia

3.2 Overview of technologies

3.2.1 Introduction

The schematic illustrates the operating principle of a green hydrogen energy storage system, which enables the long-term storage of renewable hydrogen and its reconversion into usable power. The system is designed to increase energy flexibility and resilience by coupling electricity generation, hydrogen production, storage, and electricity reconversion in an integrated process.

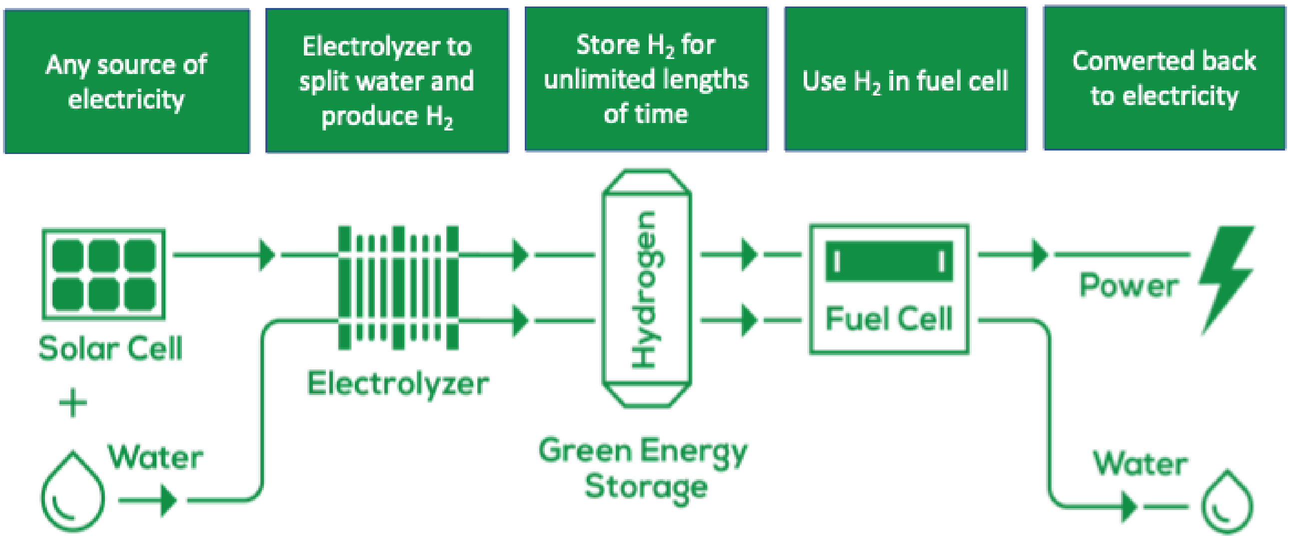


Figure 3. Schematic of the operating principle of a green hydrogen energy storage system (Source: Enapter AG)

Electricity from renewable sources, such as solar photovoltaic systems, serves as the primary energy input. This electricity is supplied to an electrolyzer, where water is split into hydrogen and oxygen through an electrochemical process. When powered by renewable electricity, the resulting hydrogen is classified as renewable hydrogen, as no fossil fuels or direct carbon emissions are involved in its production. Water required for electrolysis is supplied to the system and is reused later in the process, contributing to a closed-loop water balance.

The produced hydrogen is then stored in dedicated hydrogen storage tanks. Unlike conventional battery storage, hydrogen enables energy storage over extended and theoretically unlimited periods without significant self-discharge. This makes the system particularly suitable for bridging long-duration gaps between energy generation and demand, such as seasonal fluctuations or extended periods of low renewable generation.

When electricity is required, the stored hydrogen is fed into a fuel cell, where it reacts with oxygen from the ambient air to generate electricity. This process produces water as the only by-product and releases no direct emissions. The generated electricity can then be supplied to local loads or integrated into an electrical distribution system.

Overall, the green hydrogen energy storage system provides a sustainable solution for long-term renewable energy storage, enabling energy self-sufficiency, emission reductions, and improved system reliability, particularly in off-grid or remote applications.

3.2.2 Electrolyzer

An electrolyzer splits water (H_2O) into hydrogen (H_2) and oxygen (O_2) using electricity through a process called electrolysis. It plays a key role in green hydrogen production when powered by renewable energy sources, enabling clean energy storage and fuel applications.

Table 3 shows a comparison of the most important characteristics of different electrolyzer technologies.

Table 3. Electrolyzer technologies (Source: EGS-plan (Bangkok) Co., Ltd.)

Type	**ALK**	**PEM**	**SOEC**	**AEM**
Temperature (°C)	60 - 80	50 - 80	700 - 1000	40 - 60
Cell voltage (V)	1.8 – 2.4	1.8 – 2.2	0.95 – 1.3	1.4 – 2.0
Current density (A/cm^3)	0.2 – 0.4	0.6 – 2.0	0.95 – 1.3	1.4 – 2.0
Pressure (Bar)	< 30	30 - 70	< 25	< 35
Efficiency (%LHV)	50 - 78	65 - 82	80 - 90	57 - 65
Lifetime (Hour)	60,000 – 90,000	30,000 – 60,000	< 20,000	50,000 – 80,000
H_2 purity (%)	99.5 – 99.9998	99.9 – 99.9999	99.9	99.9 – 99.9999
System response	Seconds	Milliseconds	Seconds	Milliseconds
Price	**$**	**$$$**	**$$$$**	**$$-$$$**

Alkaline (ALK) electrolyzers have low investment costs, a high lifetime and gas purity. On the other hand, ALK are designed for large scale application and therefore the minimum capacity of these electrolyzers is too big for hotels and resorts. Therefore, ALK electrolyzers were excluded from the feasibility study.

Proton Exchange Membrane (PEM) electrolyzers have a high energy efficiency and low maintenance requirements but are costly. Nonetheless, they were considered for the feasibility study.

Solid Oxide Electrolysis Cell (SOEC) electrolyzers have a very high operation temperature and are not suitable for the application in hotels and resorts.

Anion Exchange Membrane (AEM) electrolyzers have a good scalability, good efficiency and a relatively long lifetime. On the other hand, they are relatively expensive with costs between ALK and PEM electrolyzers. Therefore, AEM electrolyzers were considered for the feasibility study.

3.2.3 Fuel-Cells

Fuel cells (Table 4) generate electricity by converting chemical energy from hydrogen (or other fuels) into electrical power through an electrochemical reaction with oxygen, producing water and heat as byproducts. They offer a clean and efficient energy source, with applications in transportation, stationary power generation, and portable devices. Unlike batteries, fuel cells continuously produce electricity if fuel is supplied, making them ideal for sustainable energy solutions.

Table 4. Fuel cell technologies (Source: EGS-plan (Bangkok) Co., Ltd.)

Type	**AFC**	**PAFC**	**PEMFC**	**MCFC**	**SOFC**
Temperature (°C)	< 100	150 - 200	50 - 100	600 - 700	500 – 1,000
Power density (W/cm^2)	Up to 0.5	Up to 0.5	Up to 4	Up to 1	Up to 1.5
Efficiency (%LHV)	60	38 - 42	30 - 60	45 – 50 Up to 85 with CHP	45 – 60 Up to 90 with CHP
Typical stack size (kW)	1 - 100	50 - 1000	<1 - 250	1 - 3000	1 - 3000
Application	• Space • Military	• Distributed generation	• Transportation • Backup power • Portable power	• Electric utility • Large distributed generation	• Auxiliary power • Electric utility • Large distributed generation
Start-up time	Fast	Slow	Fast	Slow	Slow
H_2 purity	High	Moderate	High	Low	Moderate
Price	$$$	$$	$$$	$$$	$$$

Alkaline Fuel Cells (AFCs) offer high efficiency and operate at low temperatures, but they require very high hydrogen purity and are sensitive to carbon dioxide (CO_2) contamination. This makes them unsuitable for remote island environments where maintenance and fuel conditioning capacities are limited.

Phosphoric Acid Fuel Cells (PAFCs) provide stable operation and moderate efficiency but have slow startup times and are typically available only in larger power sizes. For hotels and resorts, especially smaller facilities, their size, cost, and limited flexibility make them impractical.

Proton Exchange Membrane (PEM) fuel cells are compact, fast-responding, and efficient, with good commercial availability in the <1–250 kW range. Their low operating temperature and modularity make them excellent for hotel and resort microgrids, where flexible load-following and low maintenance are required.

Molten Carbonate Fuel Cell (MCFCs) can reach high efficiency (especially with Combined Heat and Power Plants (CHP) but operate at very high temperatures and have slow startup characteristics. They are generally deployed in large stationary systems (1–3000 kW) and require specialized maintenance not available on remote islands.

Solid Oxide Fuel Cell (SOFCs) offer fuel flexibility and high efficiencies but operate at extremely high temperatures (500–1000°C) and require complex thermal management. Their slow response times and large typical system sizes make them difficult to integrate into small, variable hotel/resort microgrids.

3.2.4 Hydrogen Generators

A hydrogen generator with an H_2 combustion engine and an electric generator produces electricity by burning hydrogen in an internal combustion engine, that drives an electric generator. This system emits only water vapor, making it a clean alternative to fossil fuels. While it benefits from existing engine technology, its electric efficiency (around 30-40%) is significantly lower than hydrogen fuel cells, which can achieve 50-60% efficiency. Despite this, hydrogen combustion engines offer robust, scalable, and carbon-free power generation, making them suitable for backup power, off-grid applications, and renewable energy integration, especially where fuel cells are impractical or costly.

Even though the hydrogen generator technology is a cost-efficient alternative to fuel cells, it was not considered to be suitable for the project in Koh Munnork. Only one supplier with small-scale hydrogen generators (< 100 kW_{el}) was found during the market research and that supplier is not exporting and servicing outside of Europe.

3.3 Investment Costs

3.3.1 Methodology

Most critical regarding the investment decision for or against green hydrogen are the upfront costs. Therefore, an important goal of the market study about green hydrogen was to determine the investment costs for the main components like electrolyzer, H2 tank and fuel cells especially considering the challenges of remote locations like off-grid islands.

To determine realistic component costs, a request for proposal (RFP) for a potential green hydrogen project in Koh Munnork was prepared.

The RFP included the following information:

- Description of the location
- Information about the HESS/BESS system including PV
- A table with a simple bill of quantities (BOQ)

Based on a preliminary sizing of the main components (see chapter 4) the following costs of components and services were requested:

- Photovoltaic system (350 kW_p, ground-mounted on difficult surface)
- Fuel cell (50 kW_{el}) incl. inverter
- Electrolyzer (4.8 kWel) incl. dryer, water tank & purification system
- H_2 Storage (45 kg)
- Battery energy storage system (800 kWh)
- EMS integration to manage the overall system consisting of fuel cell, electrolyzer, H2 tank, batteries, PV system
- Weatherproof container for the above-mentioned systems
- Shipping to Koh Munnork
- On-site installation and commissioning
- Staff training
- Customs and taxes

The request for proposal was submitted to three turnkey contractors with proven experience in Thailand and Southeast Asia. Upon receiving their responses, the proposals were thoroughly evaluated, and follow-up clarifications and additional information were requested. Thereafter the proposals were compared and evaluated to determine average component and service costs for green hydrogen system.

3.3.2 Investment Costs for HESS

Figure 4 shows a comparison of the investment costs of the main components of the hydrogen energy system: fuel cell, electrolyzer and hydrogen storage. Since the contractors partially deviated from the requested capacities and to make the costs comparable, the prices were normalized per kW_{el} and kg respectively.

All contractor proposed to install PEM fuel cells, but the capacity varies between 34.4 and 65 kW$_{el}$. The normalized costs range from 1,518 Euro/kW$_{el}$ to 3,445 Euro/kW$_{el}$. The average normalized price is 2,654 Euro/kW$_{el}$. While the 34.4 and 50 kW$_{el}$ fuel cells are similarly priced, the 65 kW$_{el}$ fuel cell shows significantly lower costs. The reason for this is most likely due to the country of origin of the 65 kW$_{el}$ fuel cell (China) compared to the 34.4 and 50 kW$_{el}$ fuel cells (Europe).

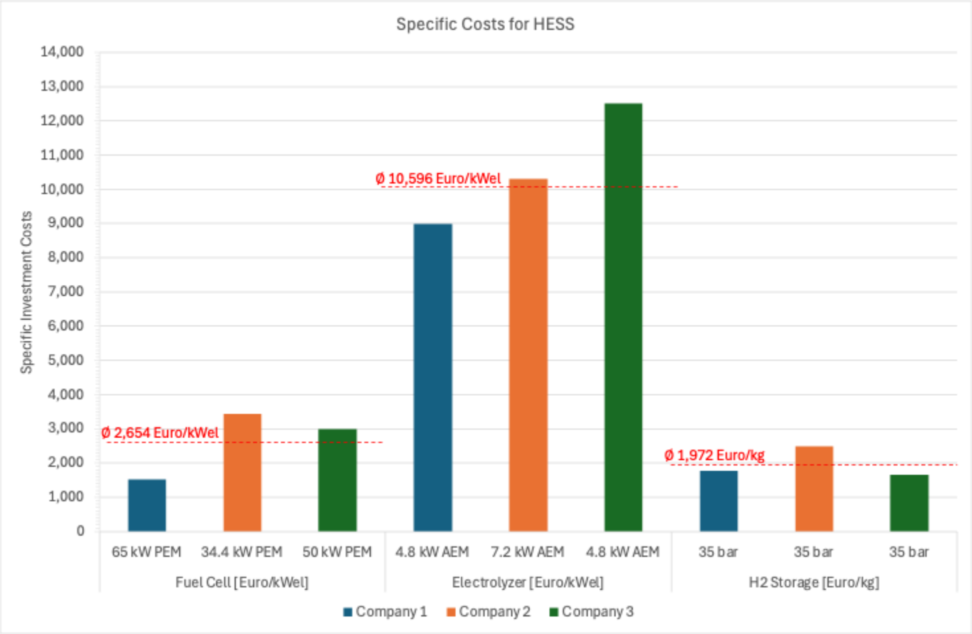


Figure 4. Comparison of investment costs for the main components of a hydrogen energy storage system (Source: EGS-plan (Bangkok) Co., Ltd.)

The prices for the electrolyzer are relatively consistent and range from 8,983 to 12,500 Euro/kW$_{el}$. This results in an average normalized price for electrolyzers of 10,596 Euro/kW$_{el}$. The reason for the consistent prices might be because they use the same technology (AEM) and most likely the same supplier from Europe.

Also, the normalized prices for the H2 tank are consistent with prices between 1,667 Euro/kgH_2 and 2,486 Euro/kg H_2. The average hydrogen tank costs are 1,972 Euro/kgH_2.

3.3.3 Investment Costs for Photovoltaic and Battery Systems

Figure 5 shows the comparison of the bids of the three contractors for the battery and photovoltaic systems.

The system price for batteries varies between 347 and 688 Euro/kWh resulting in average costs of 491 Euro/kWh which is in the higher range compared to international market prices. This can be attributed to the remote location, associated logistics and installation constraints, as well as higher system and durability requirements due to the demanding climatic conditions (hot, humid, saline environment).

Also, the photovoltaic costs range with prices between 502 and 811 Euro/kW$_p$ and an average price of 704 Euro/kW$_p$ significantly higher than normal ground mounted PV systems. The reason is the difficult installation location of the photovoltaic field at the southern tip of the island. The terrain is rocky and overgrown with bushes and the clearing of the land, and the foundation / substructure as well as the logistics are more difficult than in “normal” ground mounted PV projects. Furthermore, the PV field is located around 600 m from the resort and therefore a costly cable must be installed across the island.

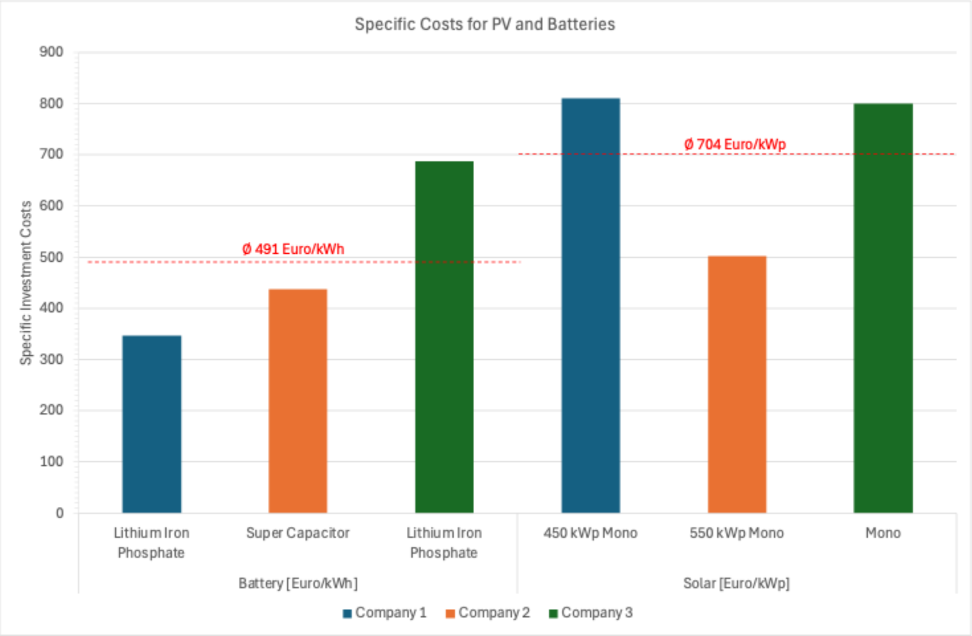


Figure 5. Comparison of investment costs for the battery and photovoltaic system (Source: EGS-plan (Bangkok) Co., Ltd.)

3.3.4 Other Costs

Energy Management System (EMS)

For the monitoring and supervision of the systems, the contracts also proposed costs for Energy Management Systems (EMS). The Energy Management Systems display the performance of the HESS/BESS system and include important real-time information, e.g. the weather conditions, solar yield, H2 tank level, battery charging level and energy consumption of the resort. More importantly, the EMS can be used for predictive maintenance and helps to find system problems. Since there is no cellular network in Koh Munnork, some bidders offer to install a satellite-based system, which also explains the large price span.

The prices for the EMS vary between 2,000 and 30,000 Euro. The average proposed price for the Energy Management System is 15,833 Euro.

Transportation, Installation and Commissioning

The transportation, installation and commissioning costs play an important role especially in remote locations like off-grid islands. The prices vary between 74,000 and 472,500 Euro. One of the reasons for this great price range is because the bidders haven’t been at the location and therefore calculated a great safety margin. The average bidding price for transportation, installation and commissioning is 233,500 Euro which is 20% of the average total system price. This is within the usual margin of cost estimations for construction projects.

3.3.5 Maintenance and Operation Costs

Reliable long-term operation requires a structured operation and maintenance (O&M) concept covering all system components as well as their interaction.

The PV system requires periodic visual inspections, cleaning of modules to remove salt spray and dust, and annual electrical checks of cabling, inverters, and protection devices. Given the island location, corrosion monitoring and proper grounding are essential. Performance data should be continuously monitored to detect degradation or inverter faults at an early stage.

The battery energy storage system (BESS) is operated via an automated energy management system (EMS). Routine tasks include monitoring state of charge, temperature, and cycling behaviour, as well as periodic inspection of battery enclosures, cooling systems, and safety equipment. Firmware updates and capacity checks are typically performed annually to ensure optimal performance and safety.

The AEM electrolyzer operates automatically during periods of surplus PV generation. Maintenance focuses on water quality management (demineralized water supply), inspection of pumps, valves, sensors, and power electronics, and regular system diagnostics. The electrolyzer stack is subject to electrochemical aging and will require replacement after its defined operating lifetime, which is accounted for in the O&M planning.

The hydrogen storage system requires regular leak checks, pressure monitoring, inspection of safety valves, and compliance with safety and ventilation requirements. All inspections follow applicable standards and manufacturer recommendations to ensure safe long-term operation.

The PEM fuel cell provides dispatchable power during periods of low solar generation. Operational tasks include monitoring load levels, temperatures, and hydrogen purity, as well as scheduled maintenance of air supply systems, cooling circuits, and power electronics. Like the electrolyzer, the fuel cell stack is a consumable component and is replaced based on operating hours.

Overall system operation is coordinated by the energy management system, which optimizes energy flows between PV, batteries, hydrogen production, and power generation. Regular data review, remote monitoring, and preventive maintenance ensure high system availability, long service life, and safe operation with minimal on-site intervention.

Local staff can be trained to carry out simple routine operations and maintenance tasks, which significantly reduces operating costs and ensures quick response on site. Typical tasks include regular cleaning of the photovoltaic modules to remove dust, salt deposits, and bird droppings, visual inspections of PV arrays, inverters, battery enclosures, and cable routes, as well as basic housekeeping of technical rooms to ensure proper ventilation and accessibility. In addition, staff can monitor system status indicators via the energy management system, report alarms or irregularities, and document maintenance activities. More complex maintenance and safety-critical work on hydrogen and electrical systems is carried out by the bidders, while local involvement ensures day-to-day system reliability and long-term performance.

Two bidders provided maintenance and operation costs for complex tasks: 10,939 Euro/a and 25,900 Euro/a. The costs do not include component replacement like batteries or fuel cell stacks. The resulting average maintenance costs are 18,419.50 Euro/a which is around 1.6% of the average total investment costs of the system.

For simple repairs, the bidders also included critical spare parts like photovoltaic modules, pumps and valves in their bids. Only bigger replacement parts like batteries, fuel cell stacks etc. require import from other countries. All bidders have trained personal in Thailand so that simple repairs can be carried out on short notice.

3.4 Financing

3.4.1 Self-Financed Investment

The financial feasibility assessment of the PV/HESS/BESS system (see chapter 4.5) shows that the proposed system has lower life-cycle costs and a lower levelized cost of energy than the diesel generator solution. However, the feasibility study also indicates that substantial upfront investment costs must be covered prior to construction. The most straightforward financing option is for the resort to fully finance these upfront costs. However, in practice, tourism operators typically prefer to allocate capital to their core business activities - such as accommodation, services, and guest experience - rather than to energy infrastructure. As a result, alternative financing and ownership models should be explored to reduce the upfront financial burden and improve overall project bankability.

3.4.2 Commercial Bank Financing

Financing by Thai commercial banks was assessed as an alternative option. In general, loans for commercial projects in Thailand are typically offered between 5.0 to 7.0 %, even for well-established businesses. While several banks provide so-called green loan products, these usually result in only a marginal reduction of the interest rate, typically in the range of a few tenths of a percentage point. Consequently, the financial benefit of green loan schemes remains limited. In the case of the Koh Munnork project, access to bank financing is further constrained by collateral requirements, as the land on which the energy system would be installed is not owned by the resort operator. As a result, the project assets cannot be used as bankable collateral, leading to a high likelihood that Thai commercial banks would decline to provide project financing under standard lending conditions.

3.4.3 Exploring Soft Loan and Grant Opportunities from Government Banks

In addition to commercial financing, government banks for redevelopment often offer soft loans and grants to support carbon-neutral energy infrastructure projects. These institutions aim to encourage the adoption of environmentally friendly technologies by offering loans at below-market interest rates or by providing partial grants. Such funding mechanisms not only reduce the financial burden of initial capital investments but also align with national or regional policy goals, such as promoting the export of domestic clean energy technologies. In the case of the Koh Munnork project, exploring these public-sector financing avenues could provide an alternative path to overcoming the challenges associated with private collateral requirements.

3.5 Conclusion

In summary, the example of the Koh Munnork green hydrogen energy system indicates that while the proposed PV/HESS/BESS system offers significantly lower life cycle and levelized costs compared to diesel generators, it does require substantial upfront capital (see chapter 4.5). Figure 6 illustrates the average investment costs for the key components, showing that fuel cells, electrolyzers, and hydrogen storage each contribute to the overall capital expenditure, alongside battery and solar investments.

In terms of maintenance, local staff can be trained to handle routine tasks, such as cleaning PV modules and performing basic inspections, ensuring day-to-day reliability. However, more complex operations - such as those involving the hydrogen system and fuel cells - require specialized maintenance, which is factored into the O&M cost estimates.

On the financing side, commercial Thai banks offer loans at relatively high interest rates, with green loans only slightly reducing the interest burden. Moreover, the lack of suitable collateral due to the resort not owning the project land makes traditional bank financing unlikely. As a result, exploring soft loans or grants from government redevelopment banks is recommended as an alternative approach to mitigate the initial financial hurdles.

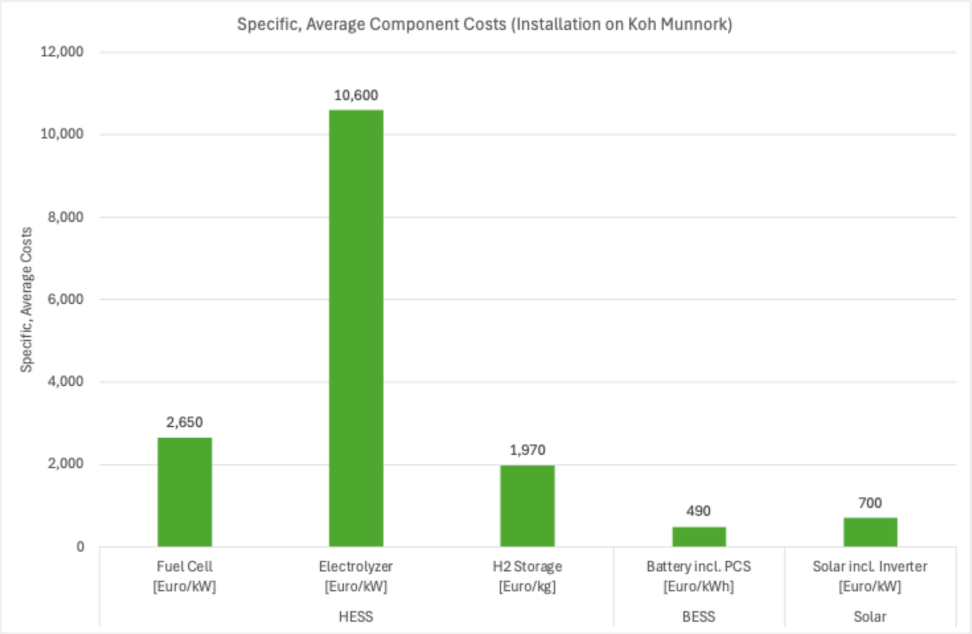


Figure 6. Average investment costs for hydrogen, battery and solar technology for Koh Munnork (Source: EGS-plan (Bangkok) Co., Ltd.)

4 Work Package 3: Feasibility Study

4.1 Introduction

4.1.1 Goals of the Feasibility Study

Work Package 3 is the core of the H2uppp project and has the following goals:

- Audit the technical condition of an existing hotel/resort or island
- Design a PV, HESS and BESS system
- Assess the technical feasibility of such a system
- Determine the economic feasibility of an energy self-sufficient supply with PV, HESS and BESS system.
- Conduct an economic optimization of such a system

4.1.2 Method

The following methodology was applied to assess the feasibility of the HESS/BESS system:

1. Collect all available technical information about the pilot project
2. Conduct energy audits to measure the electric load (if not available) and identify main energy consumers and the general condition of the resort.
3. Design a carbon-neutral energy self-sufficient supply system consisting of PV, HESS and BESS.
4. Based on the above design create RFPs (Request for Proposals) for turnkey contractor
5. Evaluate the proposals and calculate normalized costs for the main components.
6. Conduct an economic optimization of the main components.
7. Evaluate economic feasibility of the optimized option.
8. Assess technical feasibility of the optimized option.

4.2 Project Description

4.2.1 General information

Since Koh Munnork fulfils all requirements which were defined in chapter 2.1, it was selected as the pilot project. It is a small private island in the Gulf of Thailand, see Figure 7. The island has a length of around 600 m and a width of around 400 m.

The climate at the location is characterized by a tropical coastal climate with consistently high temperatures, high humidity and moderate seasonal variation (see also chapter 5.2.4). The annual mean air temperature is around 28–30 °C, with average daily maxima of approximately 33–35 °C and only small fluctuations throughout the year. Solar irradiation is generally high and well suited for photovoltaic applications, with the highest values occurring during the dry season from January to April, when average daily global horizontal irradiation reaches about 5.5–6.0 kWh/m². During the monsoon period from May to October, increased cloud cover and precipitation reduce solar irradiation to approximately 3.9–4.3 kWh/m² per day. The climatic year can therefore be divided into a dry, sunnier season with higher solar yields and a wet season with lower irradiation and higher humidity, while the temperature level remains relatively constant.

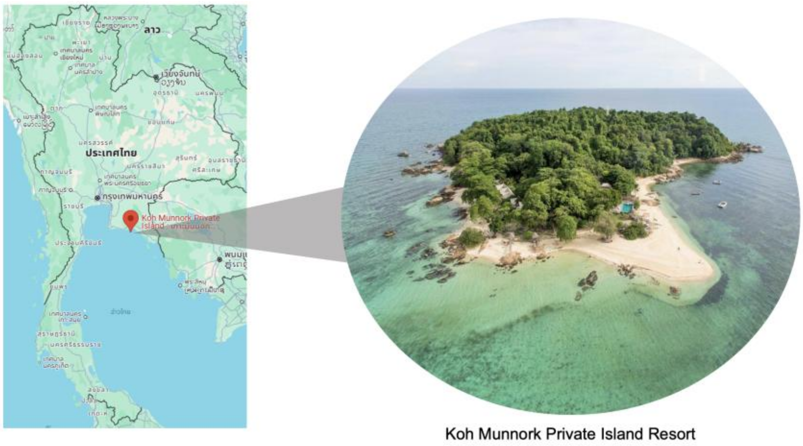


Figure 7. Location of Koh Munnork in the Gulf of Thailand (Source: Google Maps and Koh Munnork Private Island)

At the northern tip of the island is the Koh Munnork resort consisting of the main building (lobby, restaurant, kitchen, pool) and 16 bungalows with 22 units (at the west beach. 10 bungalows are detached (one unit each) and 6 are duplex with two units each. The technical and staff buildings are located around 100 m from the bungalows and the main building on a small, wooded hill, see Figure 8.

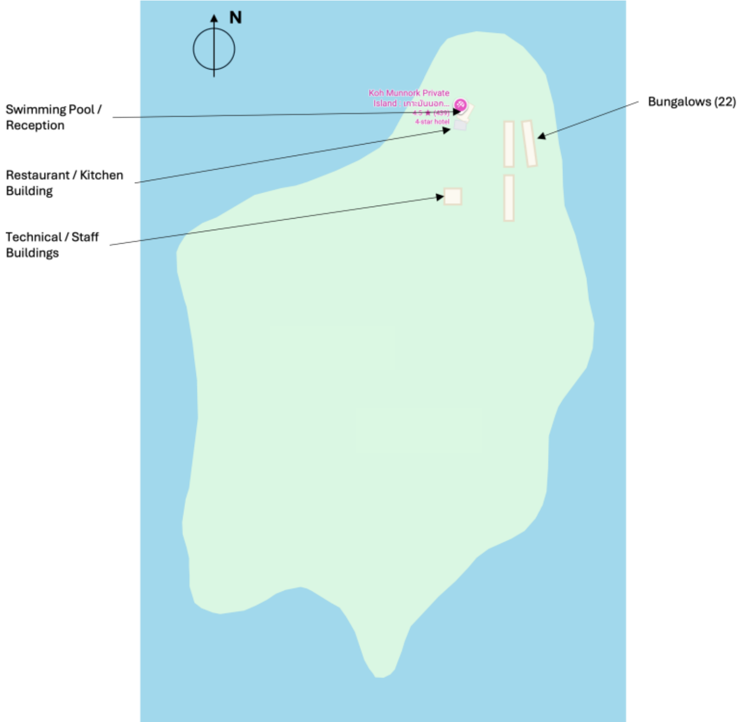


Figure 8. Koh Munnork Island and Private Resort (Source: EGS-plan (Bangkok) Co., Ltd. based on Google Maps)

The resort is marketed as an exclusive, eco-friendly retreat offering a "castaway-style" experience. Its marketing strategy emphasizes seclusion, simplicity, and sustainability, targeting travellers seeking a tranquil escape from urban life. Figure 9 shows the occupancy during the year 2024. Peak season is from November to May with occupancy rates between 70 % and 85 %. Low season is from June to October.

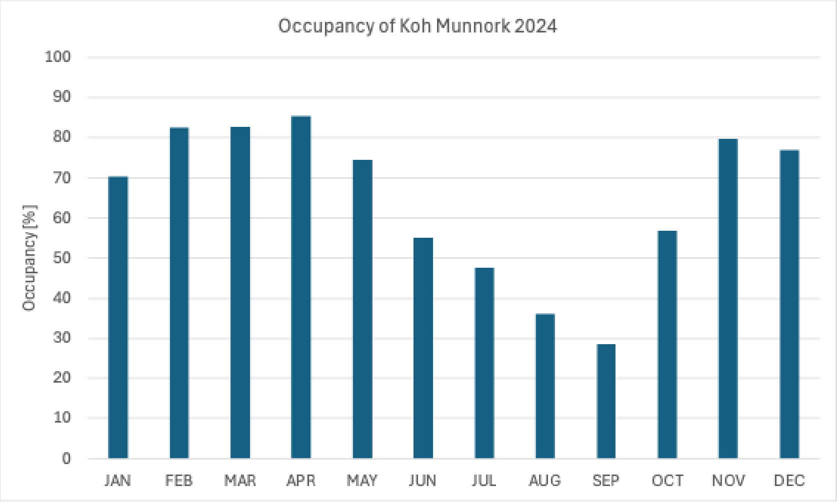


Figure 9. Occupancy of Koh Munnork in 2024 (Source: EGS-plan (Bangkok) Co., Ltd.)

4.2.2 Energy Supply Concept

The energy supply concept of Koh Munnork is based on electricity generation by diesel generator sets (gensets). Three gensets with a total electricity output of 435 kVA are installed in the technical building, see Figure 10. According to the owner, the gensets were bought second hand and a "Generator Audit Report" from 3 years ago suggests electrical efficiencies of 23 %, 24 % and 29 %. A fourth genset with 140 kVA is currently out of order. Since each genset alone has sufficient electrical power output to supply the whole resort, the gensets are operated sequentially. The gensets are switched over daily between 09:00 and 13:00 when the electricity is turned off.

160 kVA **150 kVA** **125 kVA** **Cable between Technical Building and Resort**

Figure 10. Three diesel gensets and connecting cable between the technical building and the resort (Source: EGS-plan (Bangkok) Co., Ltd.)

From the technical building, the electricity is distributed through a surface-mounted electrical cable to the kitchen / restaurant and lobby building and from there to the guest bungalows. Main electrical consumers in the bungalows are split-unit air-conditioners and domestic hot water heaters. In 5 bungalows instantaneous electric water heaters are used for domestic hot water and in the other bungalows waste heat from the air-conditioners is being used. Electricity in the bungalows is switched off from 9:00 to 13:00 to save energy. The restaurant, lobby, kitchen and staff buildings are not air-conditioned. The energy source for cooking is liquefied petroleum gas (LPG).

4.2.3 Fuel Logistics

Every day at 13:00, around 10 canisters of diesel (around 30 l each) are transported by a ferry boat from the mainland to the island along with arriving tourists, fresh water and food, see Figure 11 and Figure 12. The ferry returns to the mainland at 15:00 with returning tourists and trash.

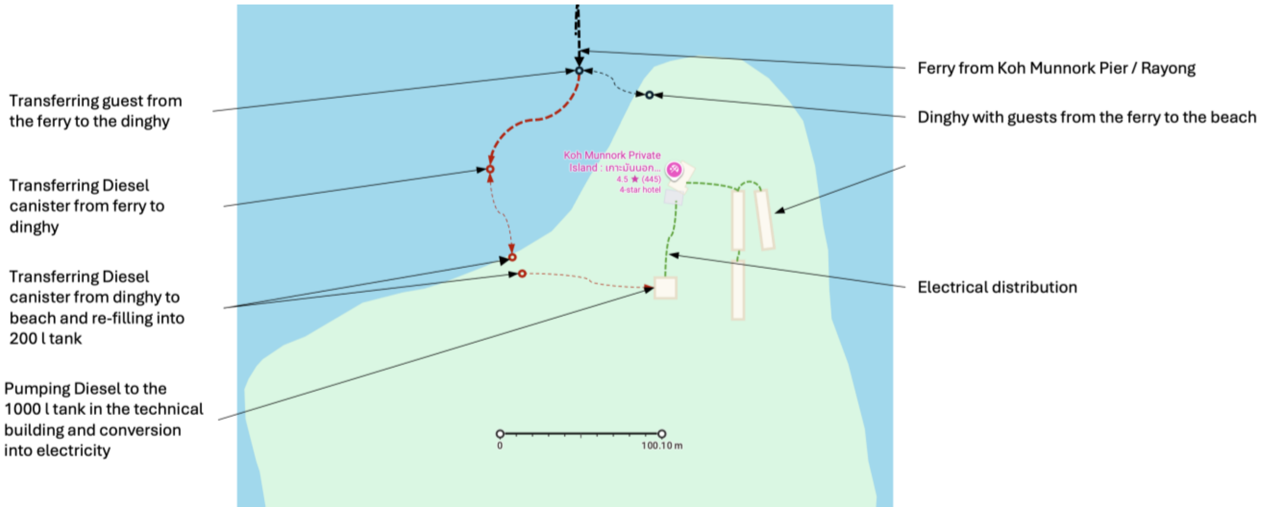


Figure 11. Fuel logistics at Koh Munnork (Source: EGS-plan (Bangkok) Co., Ltd. based on Google Maps)

After the tourists disembark, the canisters are transported by a dinghy from the ferry to the beach. At the beach is a 200-l tank which is connected to a pump. The diesel is filled from the canister into the tank and then pumped from the beach to a main tank (1000 l) in the technical building. This tank is connected to four diesel gensets of which 1 is currently not working and under repair. The active diesel gensets have an electrical power output between 125 kW, 150 kW and 160 kW.

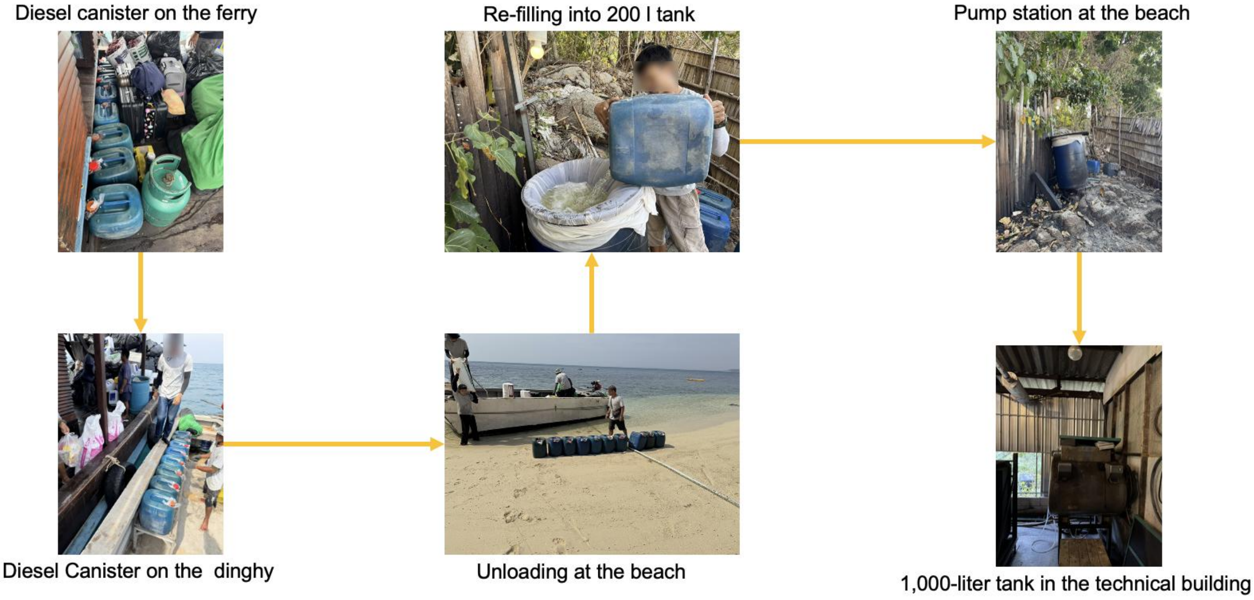


Figure 12. Photo documentation of the diesel refilling process (Source: EGS-plan (Bangkok) Co., Ltd.)

4.2.4 Environmental Impact of the Current Energy Supply Concept

Carbon emissions

Since the energy supply of Koh Munnork is based on diesel gensets, there are significant carbon emissions. The energy audit concluded that the oil consumption of Koh Munnork was in 2024 a total of 106,610 l. According to TGO (Thailand Greenhouse Gas Management Organization) the emission factor for diesel is 2.70779058 kgCO_2e/l. Hence, the carbon emissions of Koh Munnork in 2024 were 288.68 tonCO_2e.

Exhaust from the diesel gensets

The exhaust from diesel gensets contains fine dust (PM2.5, soot), nitrogen oxides, carbon monoxide, PAHs and benzene. Diesel exhaust is considered carcinogenic by the World Health Organization (WHO). This is critical due to the proximity of the staff buildings.

Environmental pollution

At the beach refuelling area, localised discoloration of the sand and adjacent wooden structures was observed, together with a noticeable diesel odour. This indicates that small quantities of fuel may occasionally be released during handling and transfer activities. Based on the site inspection, this can occur for example during the manual filtration and refilling process if the filling rate is high, or from minor leakages at pumps, pipe connections or fittings. Optimising the refuelling procedure and checking transfer equipment at regular intervals would help to further minimise such losses and improve housekeeping at the refuelling point.

Noise emissions

During the energy audit noise emission measurements were conducted inside the technical building, outside the staff buildings and outside the guest bungalows, see Figure 13.

Figure 13 Sound emission in the technical building (left: 96.7 dB) and outside (right: 90.3 dB) the staff buildings (Source: EGS-plan (Bangkok) Co., Ltd.)

During the site visit, sound pressure levels of up to 96.7 dB were measured inside the technical building. At these levels, international occupational health guidelines typically recommend the use of appropriate hearing protection for personnel working in such environments for extended periods.

In the vicinity of the staff buildings, sound levels of approximately 90.3 dB were recorded. These levels are influenced by the relatively short distance between the power generation equipment and the accommodation area, as well as the lightweight construction of the technical building. As the generators are also operated during nighttime hours, the implementation of additional noise mitigation measures — such as improved building insulation, acoustic barriers or operational optimisation — could further enhance acoustic comfort for staff.

4.3 Energy Demand Analyses

4.3.1 Annual Energy Consumption

Since there is no electric meter at the main distribution board of the resort, the annual electricity demand was calculated based on the diesel bills of 2022, 2023 and 2024 and the efficiencies of the diesel generators. Figure 14 shows the Electricity Use Intensity (EUI) for 2022, 2023 and 2024.

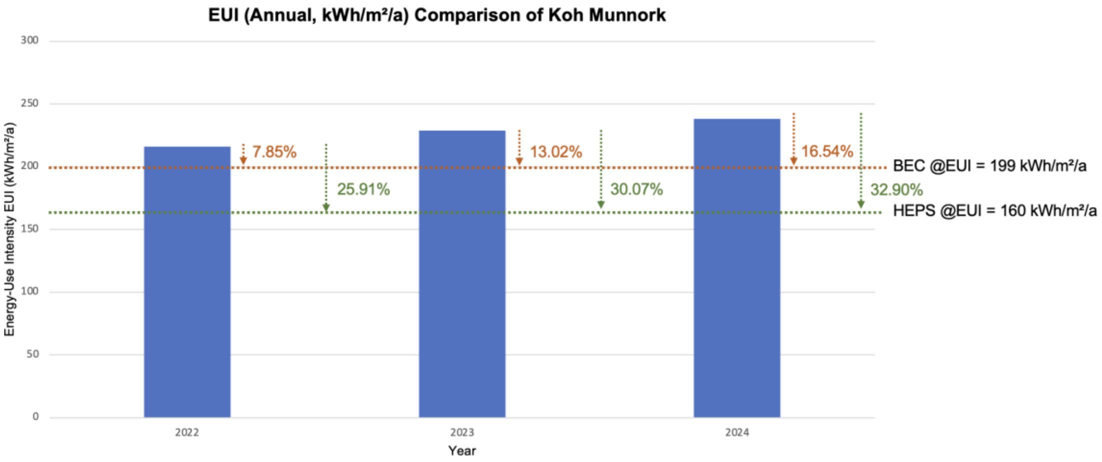


Figure 14. Electricity Use Intensity (EUI) in 2022, 2023 and 2024 in comparison BEC and HEPS standard (Source: EGS-plan (Bangkok) Co., Ltd.)

The measured Energy Use Intensity (EUI) of the resort is above the reference values provided in the Thai Building Energy Code (BEC) and the High Energy Performance Standard (HEPS) for hotels. This can be influenced by a range of factors, such as the resort's operational profile, occupancy patterns and the specific characteristics of the installed equipment and infrastructure.

From a system-optimisation perspective, it is generally beneficial to implement demand-side energy efficiency measures prior to the installation of a photovoltaic, hydrogen or battery energy storage system. Reducing the overall energy demand allows the future energy supply system to be designed with a smaller capacity, which can improve the economic performance and reduce the required investment.

Figure 15 shows the energy breakdown of the main consumers in Koh Munnork. The energy breakdown was calculated based on the installed / measured load of the energy consuming equipment, the utilization factor and an assumed operation time.

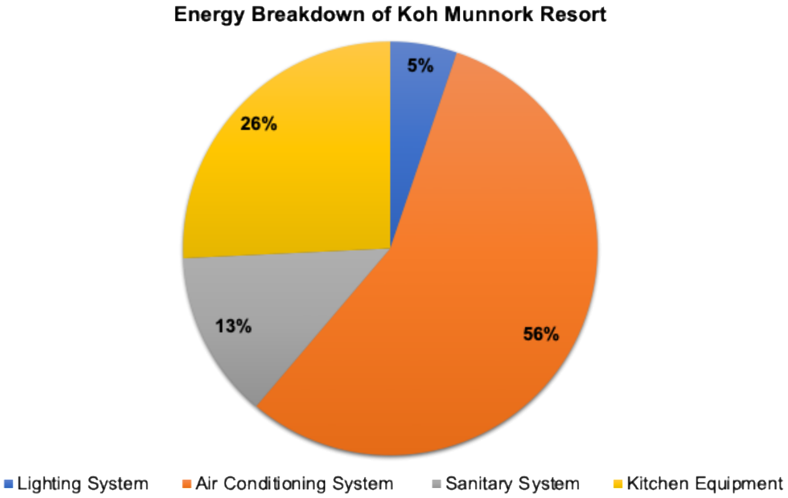


Figure 15. Energy breakdown of the main consumers in Koh Munnork (Source: EGS-plan (Bangkok) Co., Ltd.)

The main energy consumers are the air conditioners in the in the guest bungalows (56%), followed by the kitchen equipment (26%). The high energy consumption of the kitchen equipment might be caused due to the refrigerators for food storage. The sanitary systems include mainly pump equipment (freshwater, seawater, swimming pool) as well as domestic hot water heaters in the bungalows.

4.3.2 Electric Load Profile

The electric load profile of the resort is decisive for the sizing of the PV and the HESS/BESS system, because the capacity of the main components does not only depend on the total energy demand, but also when the highest demand occurs and when the highest solar yield is available.

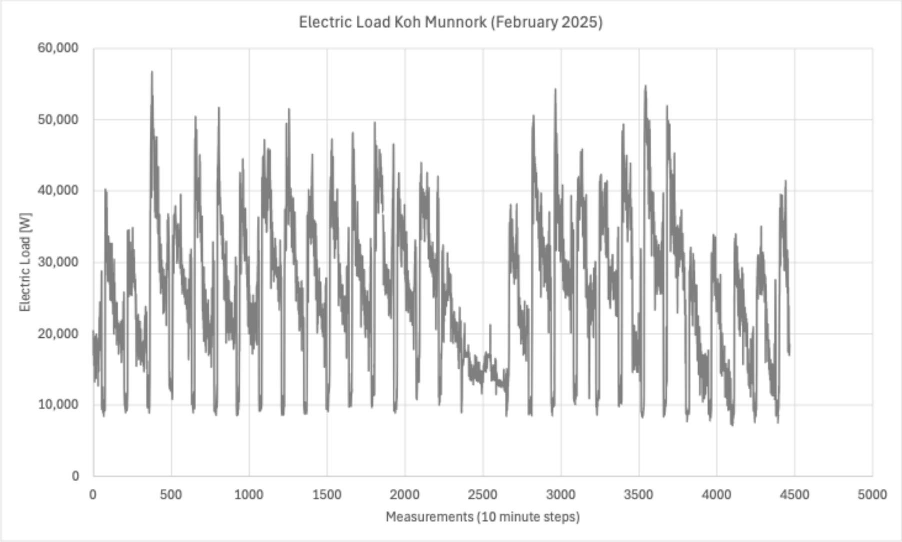


Figure 16. Measured electric load of Koh Munnork from 22.01.2025 to 25.02.2025 (Source: EGS-plan (Bangkok) Co., Ltd.)

However, no electric meter is installed at the main distribution board and hence no annual electric load curve is available. Due to the limited project timeline of one year, it was decided to measure the electric load of Koh Munnork for one month in 10-minute steps and extrapolate the load curve to one year. The measurement was conducted from 22.01.2025 to

25.02.2025 with a calibrated electric meter which was installed in the main distribution board of the resort. The load curve sufficiently reflects the electricity use patterns during day and night as well as weekends, see Figure 16.

To also consider the influence of the varying occupancy and climate influence for one year, the load curve had to be extrapolated. Therefore, the daily diesel bills of 2024 were retrieved from the resort owner. The daily diesel consumption was added up to monthly diesel consumption for 2024 and normalized by dividing the monthly diesel consumption of 2024 by the diesel consumption in February 2025. As a result, a table with utilization factors of 0.85 to 1.55 could be compiled, see Figure 17.

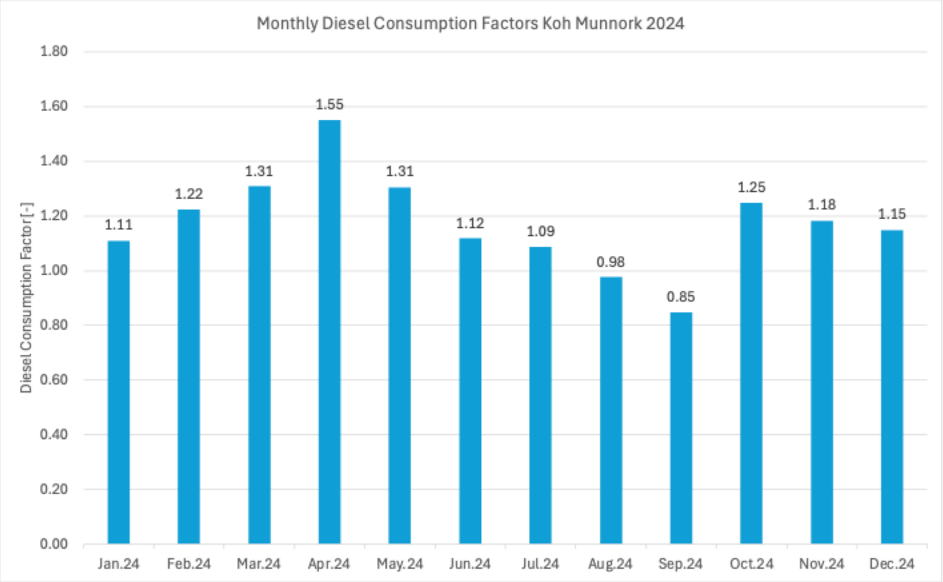


Figure 17. Monthly diesel consumption factors to reflect varying occupancy rates and climate (Source: EGS-plan (Bangkok) Co., Ltd.)

The electric load curve shown in Figure 16 was multiplied with the monthly consumption factors in Figure 17 and added up so that one annual electric load curve in 10-minute steps for 2024 could be created. Figure 18 shows the cumulated frequency of the electric load curve of the resort in 2024.

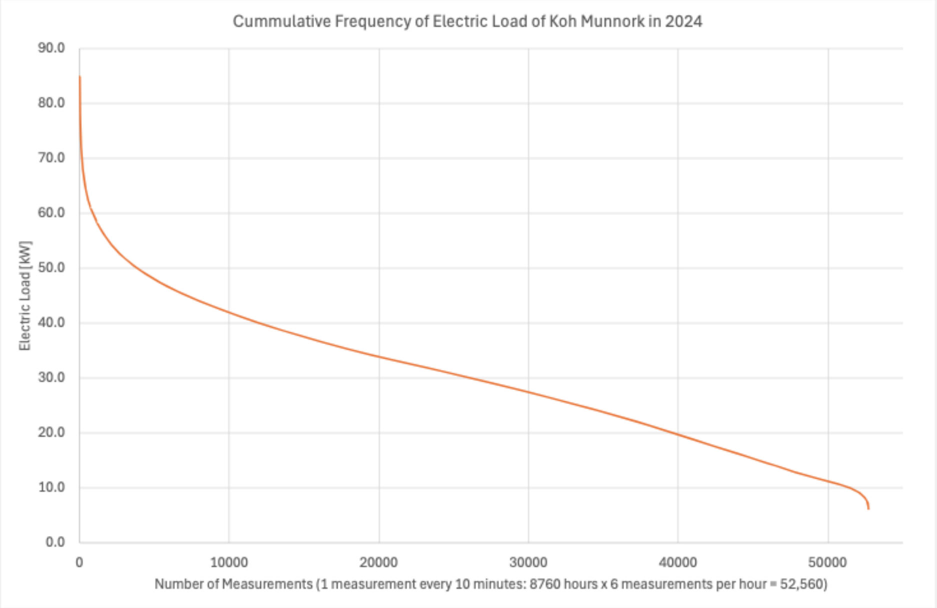


Figure 18. Cumulative frequency of the electric load of Koh Munnork in 202 4 (Source: EGS-plan (Bangkok) Co., Ltd.)

4.4 Design and simulation of the self-sufficient energy supply

Figure 19 shows the suggested energy self-sufficient supply system for Koh Munnork. A photovoltaic system generates 100% of the island's total electrical energy consumption and supplies it either directly to the resort via the inverter and main distribution board or, in the case of electricity overproduction, to the bi-directional controller (PCS). For short term energy storage (e.g., day – night), the electricity is supplied from the PCS to the battery energy storage system (BESS). For long term energy storage (e.g., longer periods of overcast days), the electricity is supplied from the PCS to the hydrogen energy storage system (HESS). The electrolyzer of the HESS system converts the electric energy to hydrogen and supplies it to the hydrogen tank. In case of one or more days with overcast sky and low solar production, the hydrogen is reconverted to electricity and supplied to the resort. Thereby the resort is supplied by renewable electricity all year long without interruptions. The auxiliary systems of the BESS and HESS (e.g. the RO plant or AC) are supplied by electricity from the MDB-Load since it permanently provides electricity.

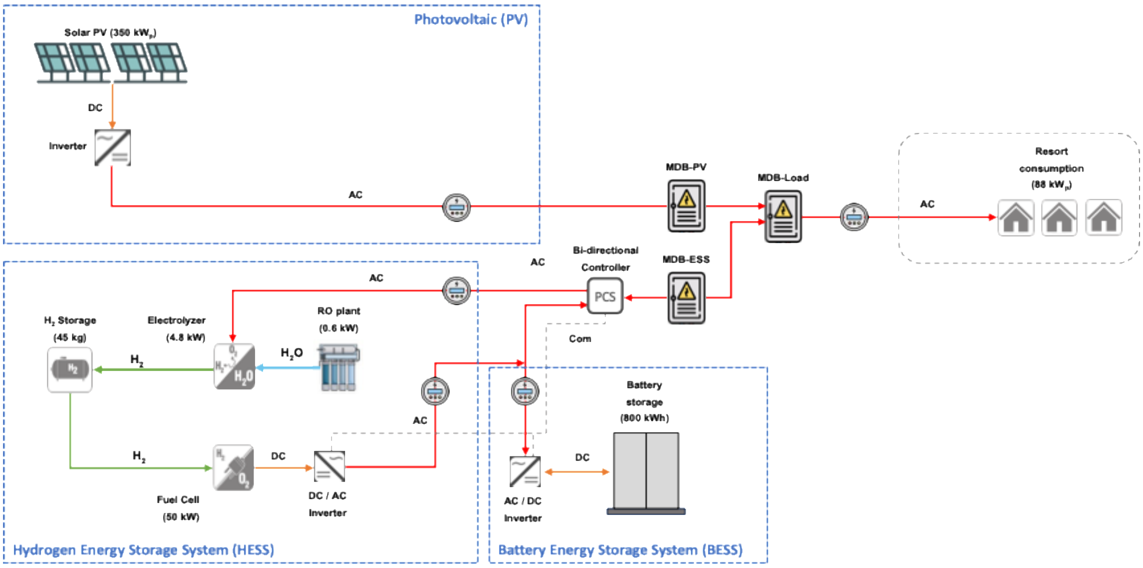


Figure 19. Suggested energy self-sufficient supply for Koh Munnork (Source: EGS-plan (Bangkok) Co., Ltd.)

The most important task during the pre-design of the above system is the economic optimization of the main components PV – HESS – BESS due to their different investment costs, efficiencies, lifetimes and other factors. To conduct this optimization, process an Excel-based tool was developed.

The starting point for the optimization was the electric demand curve of the resort in 10-minute steps and the resulting annual electricity demand of 266 MWh/a. The Excel tool compares the demand side (annual electric load curve) with the supply side (solar yield) and prioritizes the supply of electricity to the resort directly. In case of an electricity surplus, the BESS or HESS system is being charged. During nighttime or on days with insufficient solar yield electricity is supplied with priority from the battery system (short-term storage). In case the battery is discharged and there is still no solar yield, the system switches to the HESS system and discharges the H2 tank (long-term storage). The main components are represented by columns in the Excel tool and energy balances are calculated in 10-minute steps.

The tool provides the possibility to easily modify the capacities of the main components, so that an economic optimization of the system was possible (see chapter 4.5). Important technical assumptions such as electrolyzer and fuel cell efficiencies are shown in annex 8.2. The economic optimization of the system was done with the goal avoid power outages with the smallest main component size possible. The following table shows the minimum component size accordingly:

Photovoltaic system:	425 kW$_p$	Electrolyzer:	4.8 kW$_{el}$
Battery:	800 kWh	H_2 Storage:	52.5 kg
		Fuel cell:	63 kW$_{el}$

With the suggested system no power outages occur. Figure 20 shows the resulting annual energy balance of the suggested carbon-neutral energy supply system.

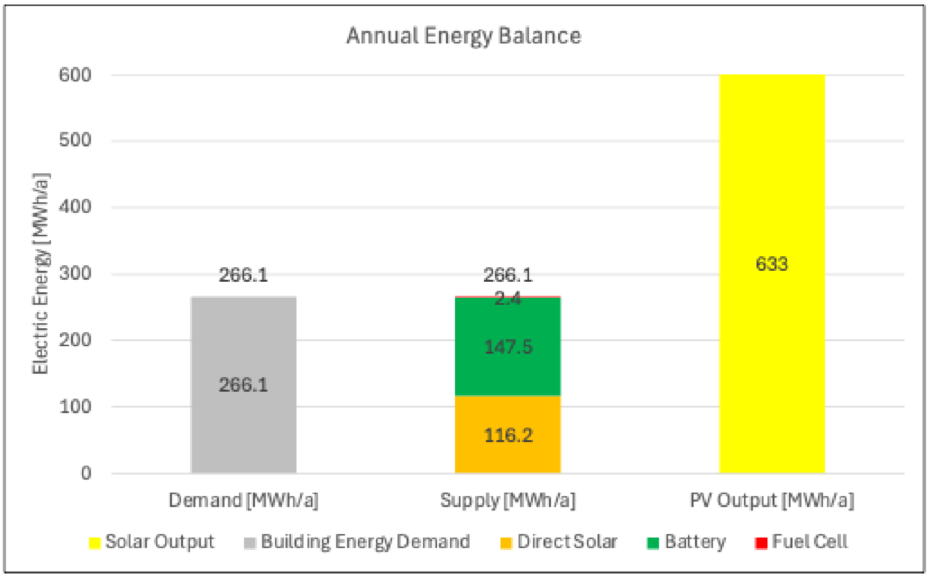


Figure 20. Annual energy balance of the suggested energy supply system for Koh Munnork (Source: EGS-plan (Bangkok) Co., Ltd.)

The annual electric energy demand of the resort is 266 MWh/a. Around 44% are covered by direct solar gains from the PV system. The total solar production is more than double of the electricity demand (633 MWh/a). The reason for the over dimensioning of the PV system is the need to provide sufficient energy also during days with overcast skies. 55% of the energy demand is covered by the battery system during nighttime and overcast sky with insufficient solar generation. Around 1% is provided by the hydrogen system, which gives it the characteristics of an emergency generator during several days with reduced solar radiation.

Figure 21 shows the most critical week of the year with low solar radiation during three consecutive days with a high electric load by the resort. Both battery and hydrogen tank are almost empty on day 5. The upper load curves show at the bottom the demand curve of the resort and how the demand is covered by direct solar radiation (brown), battery (green) and hydrogen (green, lower diagram). The upper group of curves show the solar production and the battery status. The lower diagram shows the status of the hydrogen tank and the charging and discharging processes.

At the beginning of the week the battery is fully charged (800 kWh), but the hydrogen tank is only around 50% full (28 kg). The upper diagram shows how the battery is fully charged daily until the 4th day. During the following two days the battery is discharged (5%) at the end of each day. On these days, the resort is supplied by electricity from the fuel cell (green curve, bottom diagram). After the second day of discharging the H2 tank, the tank is almost empty, but the recharging starts slowly on the next day (blue curve, bottom diagram), while the battery is already fully charged again.

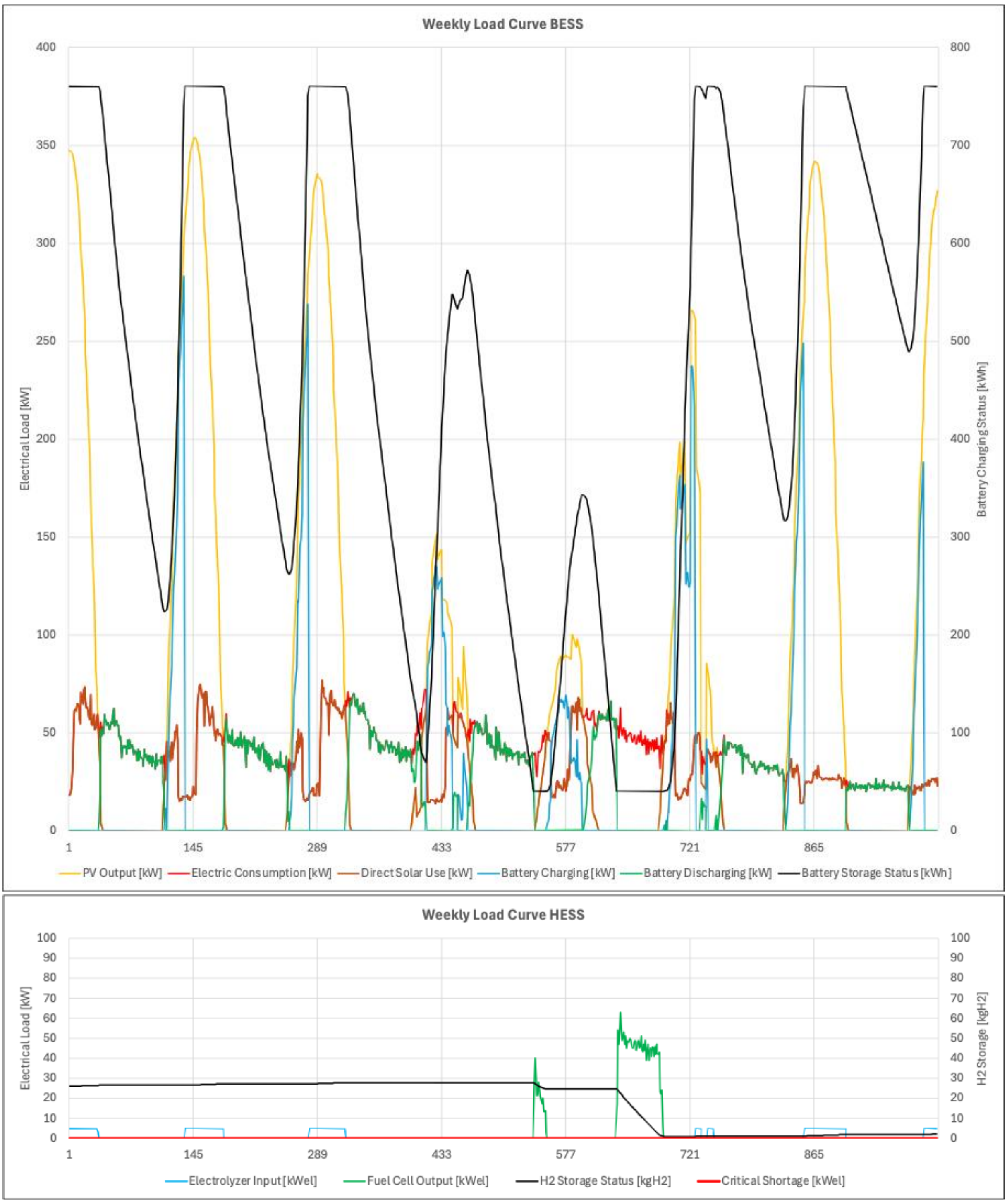


Figure 21. Load curves during the most critical week of the year (Source: EGS-plan (Bangkok) Co., Ltd.)

4.5 Economic Optimization of the Energy Supply

4.5.1 Goals

The main goal of the project was to assess the economic feasibility of the suggested carbon-neutral and self-sufficient energy supply consisting of PV, HESS and BESS in comparison to the current diesel generator system. The HESS and BESS systems are both energy storage systems, but with very different characteristics in terms of investment costs, efficiencies, lifetime, degradation and other factors. Therefore, 3 options were developed with different sizes of HESS and BESS systems with the goal to reduce the life-cycle costs (LCC) and the levelized costs of energy (LCOE). All three options fulfil the main goal of self-sufficiency (0 blackouts) per year.

4.5.2 Evaluated Options

Table 5 shows the component capacities for Option 0 through 3. Option 0 serves as the baseline, representing an energy supply by diesel generators. To ensure a fair comparison with the current situation, we assume the cost of new units matches the capacities of the existing generators.

Table 5. Sizing of the main components of options 0 to 3.
Source: EGS-plan (Bangkok) Co., Ltd.

	Option 0 (baseline)	**Option 1 (800 kWh BESS & 1,750 kWh HESS)**	**Option 2 (1,750 kWh BESS & 0 kWh HESS)**	**Option 3 (550 kWh BESS & 2,500 kWh HESS)**
Photovoltaic	Diesel Generator	425 kW$_p$	425 kW$_p$	425 kW$_p$
Electrolyzer		4.8 kW	-	43.2 kW
H2 Tank		1,750 kWh (52.5 kg)	-	2,500 kWh (75 kg)
Fuel Cell		63 kW	-	63 kW
Battery		800 kWh	1,750 kWh	550 kWh

Option 1 is an option with a relatively large battery storage. The size of the battery was designed to cover the energy demand during nighttime to serve as a short-term storage. The hydrogen system is used as an "emergency generator" to cover days with low solar irradiation and when the battery runs low (long-term). Therefore, the expensive electrolyzer is sized relatively small (4.8 kW) because the hydrogen can be produced during most of the year and accumulated in the hydrogen storage. In case there is no direct solar irradiation and the battery storage is empty (5%), the fuel cell can cover almost the complete load of the resort (up to 63 kW).

Option 2 is an option without a hydrogen system and only a battery which would significantly reduce the number of different technical components and hence the complexity of maintenance. The system only consists of the photovoltaic system (425 kW$_p$) and the battery storage with a size of 1,750 kWh. The battery is covering both short-term and long-term energy storage purposes.

Option 3 is a HESS/BESS system like option 1, but with a significantly larger hydrogen system and a smaller battery. The capacities of the electrolyzer and fuel cell were derived from an off-the shelf integrated system which is available on the market. The electrolyzer capacity in the system is 42.3 kW and the capacity of the H2 tank had to be increased to 2,500 kWh accordingly. The capacity of the fuel cell stays at 63 kW. In this case the hydrogen system serves as the long-term storage and partly as the short-term storage. The idea is to benefit from the longevity and lower degradation of the hydrogen components.

The Excel tool was used to optimize the capacities of all three options. Any further reduction of the capacities of the PV, HESS and BESS system would lead to blackouts.

4.5.3 Technical and Economic Boundary Conditions

The simulations to calculate the size of the main components were carried out based on the Excel tool which was described in chapter 4.4. The options were optimized manually with the goal to achieve no critical shortage but low life-cycle costs. The following technical and financial boundary conditions were integrated into the tool so that the life-cycle costs (LCC) and levelized cost of energy (LCOE) were calculated automatically depending on the capacity of the main components.

For the battery system Lithium-Ion batteries were considered. The charging level of the battery was assumed to be 100% at simulation start. The maximum discharging and charging levels were limited to 5% and 95% respectively. The lifetime of the batteries was calculated depending on the number of discharging cycles.

The charging level of the H2 tank was 50% at simulation start. This is important because especially for option 1 with a small electrolyzer, the charging of the tank takes a couple of weeks. The charging and discharging level of the tank was not limited. The electrolyzer efficiency was assumed to be 63% (average efficiency of AEM electrolyzers) and the fuel cell 50%.

Regarding the financial boundary conditions an inflation rate of 2 % was assumed which is in line with the Bank of Thailand's medium-term inflation target range of 1–3 % and reflects the midpoint of the official price stability band. Furthermore, a real discount rate of 6 % has been assumed for the economic evaluation. This value corresponds to the social discount rate typically applied in Thailand for public project appraisal and is consistent with the 5–9 % range recommended by ADB and the World Bank for infrastructure and energy projects in developing economies. The life-cycle costs were calculated with an assumed project lifetime of 20 years. The Diesel price increase is assumed to be 3%. Table 6 shows the O&M costs and lifetime of each main component of the systems.

Table 6. Assumed O&M costs and component lifetime (Source: EGS-plan (Bangkok) Co., Ltd., based on VDI 2067 and manufacturer data)

	Operation & Maintenance Costs (Percent of Investment Costs)	**Lifetime**
Diesel Genset	10%	10 years
Fuel cell	2%	Calculated based on charging cycles
Electrolyzer	3%	Calculated based on charging cycles
H2 Tank	1%	30 years
Battery	1.5%	Calculated based on charging cycles
Photovoltaic	1%	25 years

4.5.4 Investment Costs

Figure 22 shows a comparison of the investment costs for the different systems based on the average component costs from the tendering process (see chapter 3.3.2 and 3.3.3) and the capacities of the main systems as listed in Table 5.

The investment and installation costs for the new diesel generator sets were requested from an equipment supplier (N2F Power Generator Services Ltd.) and the bid was with 127,000 Euro around 10 times lower than the other three options. The lowest investment cost of the carbon neutral energy supply solutions has option 1 with total investment costs of 1.14 million Euro. The most expensive component for this solution is the battery storage, followed by the photovoltaic system.

Around 11% percent more expensive is the solution with a 100% battery storage and no green hydrogen. The total costs are 1.27 million Euro, and the battery system is by far the biggest cost position.

With 1.43 Millio Euro option 3 is 26.1% more expensive than option 1. In this case the electrolyzer is the most expensive component, while the cost for the H2 tank and the fuel cell are almost the same as in option 1. The battery is cheaper than in option 1 but cannot compensate the higher electrolyzer costs.

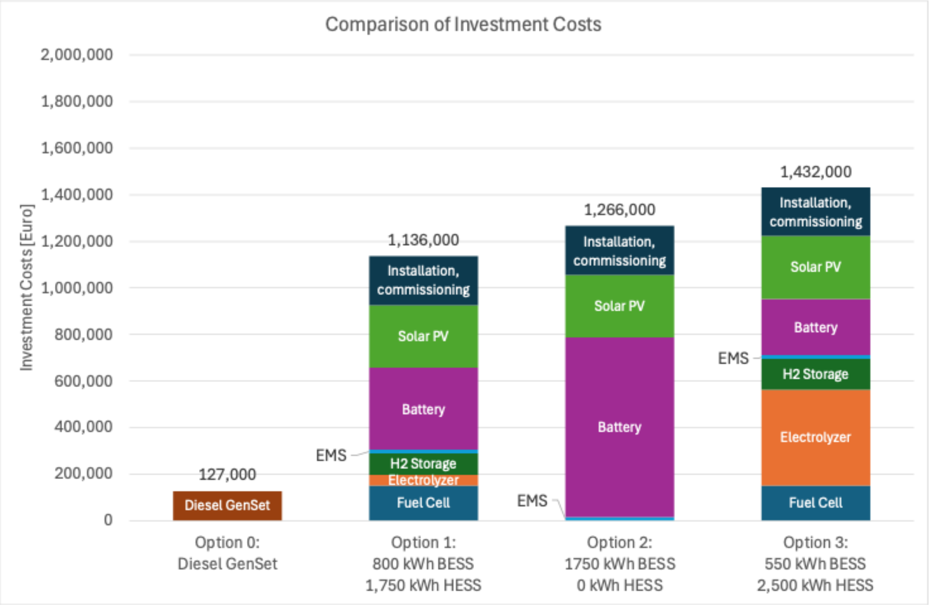


Figure 22. Comparison of investment costs of the main components (Source: EGS-plan (Bangkok) Co., Ltd.)

4.5.5 Life-Cycle Costs (LCC)

Figure 23 shows a comparison of the life-cycle cost of option 0 to 3. The life-cycle costs were calculated according to the net present value (NPV) method considering the economic boundary conditions as mentioned in chapter 4.5.3 and Annex 8.2. Thereby not only the capital costs are considered, but also the fuel prices, maintenance and operation costs as well as replacement costs which are especially crucial for battery systems and stack replacement.

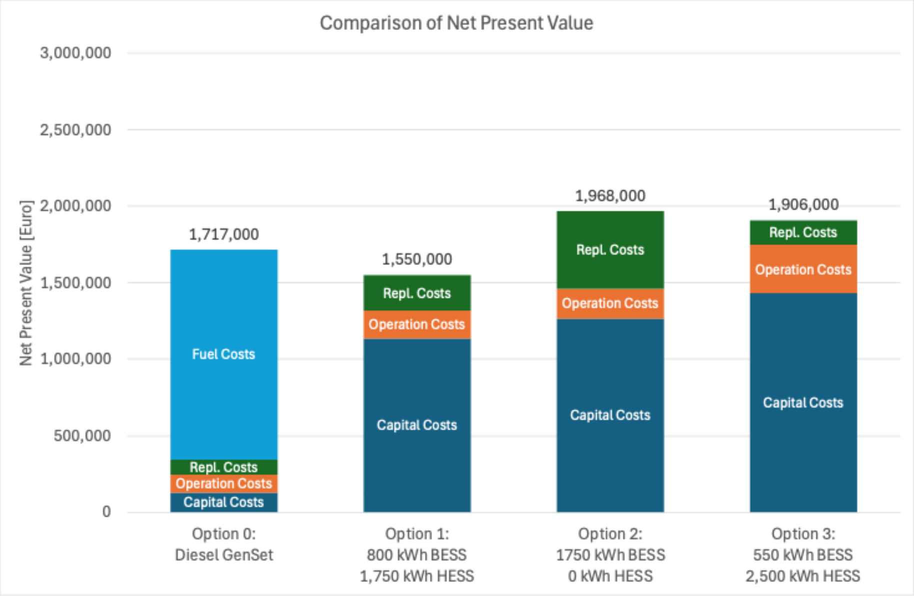


Figure 23. Comparison of the net present value (NPV) of option 0 to 3 (Source: EGS-plan (Bangkok) Co., Ltd.)

While option 1 to 3 are dominated by high capital costs, the life-cycle costs for option 0 (Diesel GenSet) are dominated by diesel fuel costs.

Option 1 with a reduced hydrogen system is economically the most efficient option and is even cheaper than option 0 with diesel gensets. Option 2 with batteries only has the highest life cycle costs due to the large and expensive battery which must be replaced once within 20 years. Option 3 with a larger hydrogen system has slightly lower life cycle costs than the option 2 but is still more expensive than option 1 with a reduced hydrogen system.

4.5.6 Levelized Cost of Energy (LCOE)

Figure 24 shows a comparison of the LCOE of options 0 to 3. The assumptions underlying the LCOE calculation are presented in Annex 8.2. The LCOE of option 0 is 0.52 Euro/kWh electricity. This is about four to five times higher than the average electricity costs in Thailand. The price difference is due to the high fuel costs for diesel and the high maintenance costs of the generators.

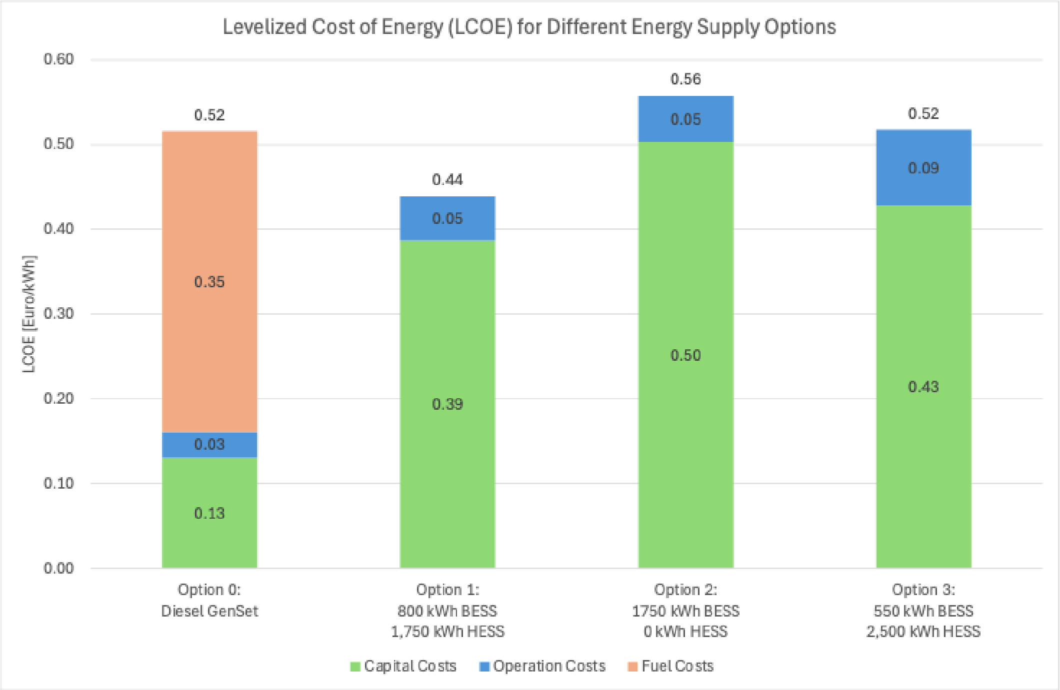


Figure 24. Comparison of levelized costs of energy (LCOE) (Source: EGS-plan (Bangkok) Co., Ltd.)

With 0.44 Euro/kWh option 1 with a combined battery and hydrogen system, has significantly lower LCOE then the option with diesel generators. Option 2 with a large battery system has the highest LCOE due to the high capital and replacement costs for the batteries. Option 3 with a larger hydrogen system than in option 1 leads to similar LCOE as option 0 with diesel gensets.

4.6 Technical Implementation

4.6.1 Technical Concept

The economic assessment demonstrates that a self-sufficient, carbon-neutral energy supply for Koh Munnork is both technically feasible and economically viable. The recommended system architecture combines hydrogen-based long-term energy storage (HESS) with a battery energy storage system (BESS) for short-term balancing and high-efficiency power management. This hybrid configuration enables a reliable energy supply under fluctuating renewable generation conditions.

Figure 25 illustrates the proposed technical concept, including the system topology and the dimensioning of the main components. The indicated capacities result from an economic optimisation and represent the minimum required values.

Depending on the availability of commercial components and final engineering design, individual component sizes may deviate from these baseline values.

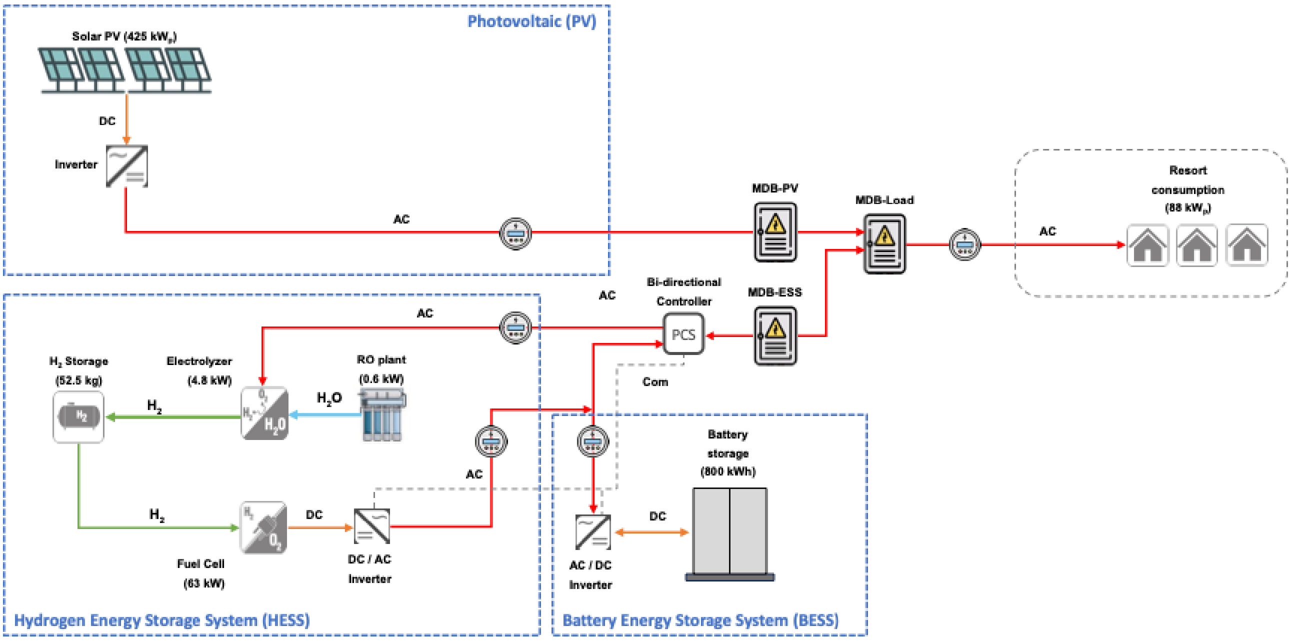


Figure 25. Single line diagram and capacities of the main components (Source: EGS-plan (Bangkok) Co., Ltd.)

The suggested PV system has a total capacity of 425 kW_p and consists of highly efficient monocrystalline solar modules with a total net-area of around 2000 m^2. The PV inverter hast to be located close to the PV field to reduce energy loss of the cables. The AC cable from the PV system is connected to the bi-directional controller in the technical centre which manages the flow of energy to the battery and hydrogen systems as well as the resort. The battery system has a storage capacity of 800 kWh. The hydrogen system consists of the electrolyzer (4.8 kW), the hydrogen tank (52.5 kg) and the fuel cell (63 kW) as well as the cooling systems, the reverse osmosis plant (0.6 kW) and the required safety systems. The auxiliary systems of the BESS and HESS (e.g. the RO plant or AC) are supplied by electricity from the MDB-Load since it permanently provides electricity. Furthermore, electric meters and other sensors as well as the energy management system are integrated in the technical centre.

The installation site of the PV system is planned in the southern part of the island (see Figure 26). This location is suitable as there are no guest accommodations in this area and the available space is sufficiently large and relatively flat. Towards the sea, the area is rocky, while towards the inner part of the island there is vegetation in the form of bushes and shrubs up to about waist height. This vegetation would have to be removed for the installation of the PV system. A particular challenge of this location is the absence of a suitable landing area for boats due to the rocky coastal structure. Therefore, the modules and construction elements must be transported across the island. In addition, suitable measures must be taken for the temporary storage of the modules and to protect them from damage and environmental influences, in particular moisture and salty air.

According to manufacturer´s specifications, the hydrogen infrastructure is primarily based on containers which can be used both for logistics and later as the housing of the system. Two 10-foot container (each 3.1 × 2.4 × 2.6 m; L × W × H) are considered to be sufficient. The container integrates the electrolysis plant, the fuel cell, a small battery storage unit and the associated balance-of-plant components, including cooling systems, a reverse osmosis plant, inverters, and safety systems (ventilation). The hydrogen storage unit, and the additional battery storage system are to be installed separately from the container. The location of the technical centre is protected against seawater and extreme weather events due to its location in the centre of the island. In addition, the technical equipment at this location is not visible to guests. The disadvantage is that this installation site is located on a hill that must be climbed from the beach.

Figure 26. Location of the main components (Source: EGS-plan (Bangkok) Co., Ltd. based on Google Maps

4.6.2 Logistics

A car ferry with a bow ramp and low draft is a suitable option to transport the hydrogen infrastructure to the island, see Figure 27. The ferry can be loaded with the equipment on the mainland. For the crossing to Koh Munnork, a suitable weather window with calm seas and the highest possible water level during high tide is required, allowing the ferry to approach as close to the shoreline as possible. After docking, the bow ramp can be extended and the equipment unloaded. For further distribution of the components on the island, appropriate preparation of the transport route is necessary. To ease the transport of containers and system components over the sandy ground, a temporary and modular steel ramp or a temporary construction road made of plastic panels can be used. This allows the containers to be brought ashore either using a forklift truck supplied with the shipment or, alternatively, with the aid of heavy-duty rollers and the caterpillar available on the island.

Figure 27. Transport logistics for the implementation of the system.
Sources left to right: EGS-plan (Bangkok) Co., Ltd. with AI, Baumann Logistik GmbH & Co. KG, GEIER GMBH, SONNENSHOP.DE

The existing path leading from the beach to the technical building should be widened to allow passage of the container width. This might require the removal of bushes and shrubs, as well as levelling uneven sections by adding gravel. The plastic panels can then be laid as a temporary construction road. The actual transport can be carried out using the caterpillar. Due to the transport over elevated terrain, it must be ensured that the construction road is flat, load bearing and sufficiently stable to guarantee the safe transport of the heavy components. For further planning, investigations into the load-bearing capacity of the ground and the loads that occur are also necessary.

A temporary transport route must also be set up to move the PV modules from the landing spot of the transport ship to their intended installation site at the southern tip of the island. There is an existing footpath around the island which can be used for this purpose. Due to the smaller dimensions of the modules, this path does not need to be as wide as the one for container transport. Nevertheless, vegetation removal and ground levelling may also be necessary. The planned PV system, with a capacity of approximately 425 kW, requires around 950 modules and an installation area of approximately 2,000 m². These modules can be transported in batches to the southern part of the island using the tracked load carrier.

4.6.3 Permitting Procedures and Local Authorities

The land of Munnork Private Island Hotel is owned by the Treasury Department under the Ministry of Finance and leased for a limited time by the operator of the resort. Also, the island falls within the jurisdiction of the Royal Thai Navy, any activities or developments by the hotel must receive prior authorization from the Navy. Since the installation of a PV/HESS/BESS system requires elaborate logistics and construction activities, approvals from the local government might be required as well.

Due to the involvement of 3 governmental authorities an early start of communication prior to the installation is required to avoid unforeseen approval issues.

5 Work Package 4: Parameter Study

5.1 Goals and Methodology of the Parameter Study

5.1.1 Objectives

The objective of Work Package 4 (WP4) was to evaluate the transferability and robustness of the carbon-neutral, energy self-sufficient supply concept developed for Koh Munnork. While the detailed system design presented in Work Package 3 is based on site-specific conditions in Rayong, Thailand, WP4 aims to assess whether the same technical concept can be applied to other locations in Southeast Asia with comparable success.

In particular, the work package investigates how climatic conditions and local fuel prices influence:
- electricity demand,
- system sizing requirements,
- investment and life-cycle costs, and
- overall economic feasibility.

By addressing these aspects, WP4 contributes to the broader objective of identifying replicable and scalable solutions for off-grid hotels, resorts, and small islands in the region.

5.1.2 Methodological Approach

WP4 is based on a model-driven, comparative approach. A detailed energy simulation model of the Koh Munnork resort was developed and calibrated using measured electricity consumption data for the year 2024. The purpose of this calibration was to ensure that the simulation accurately represents real operating conditions, including building characteristics, occupancy patterns, and cooling demand.

Once calibrated, the simulation model was used as a reference model and applied to other Southeast Asian locations by substituting the local weather datasets. This approach allows isolating the impact of climate while keeping all other parameters constant.

The resulting location-specific electricity load profiles were then combined with local solar irradiation data in a dedicated sizing and economic evaluation tool. This tool was used to adapt the main components of the PV/HESS/BESS system with the following objectives:

- ensuring uninterrupted power supply,
- maintaining 100% energy self-sufficiency, and
- minimizing life-cycle costs.

For comparability, investment costs were assumed to be similar across the assessed countries, reflecting the largely international supply chains for PV, batteries, and hydrogen technologies. In contrast, diesel fuel prices were adjusted to local conditions, as they are a key driver of economic performance.

5.2 Simulation Model Description

5.2.1 Simulation Tools and Data Sources

The simulation model was developed using DesignBuilder V6, a widely applied building performance simulation software. DesignBuilder enables the assessment of energy demand, thermal comfort, and system performance and is frequently used in international energy efficiency and climate projects.

Meteorological input data for the year 2024 were generated using Meteonorm and converted into EPW format, which is compatible with DesignBuilder. Meteonorm provides long-term, location-specific climate data and is well suited for comparative analysis across different regions.

5.2.2 Building Typology and Physical Characteristics

To accurately represent the resort, the buildings on Koh Munnork were classified into ten distinct building types based on their architectural characteristics and electricity consumption patterns. Buildings with similar geometry, construction, and usage - most notably the guest bungalows - were aggregated into three representative categories to reduce model complexity while maintaining accuracy.

Each building type was modelled individually, considering:

- envelope construction and thermal properties,
- glazing ratios and shading,
- internal equipment loads, and
- cooling system characteristics.

The resulting building physics assumptions are illustrated in Figure 28, while detailed input parameters are documented in annex 8.3. The total number of bungalows is 16 with 22 units. Type J and Q (total: 10) are detached with one unit per bungalow. Bungalow type B (total 6) is duplex (two units each).

Model Reference: Architectural Drawing + Site visit photo documentation
Software: DesignBuilder V.6
Weather file: Recorded 2024 Rayong/ U-Taphao (Meteonorm)

Envelopes	Material	U-value (W/m2K)
External wall	100mm thick plaster paint on brick wall	3.39
Internal wall	100mm thick plaster paint on brick wall	3.39
Glazing	Single glazing – Clear glass	U = 5.80 SHGC = 0.83 VLT = 0.88
Roof	Roof tile + 9mm gypsum ceiling	5.37
Floor	150mm concrete + tile finishing	2.64
Overhang and shading	Dimension according to design	

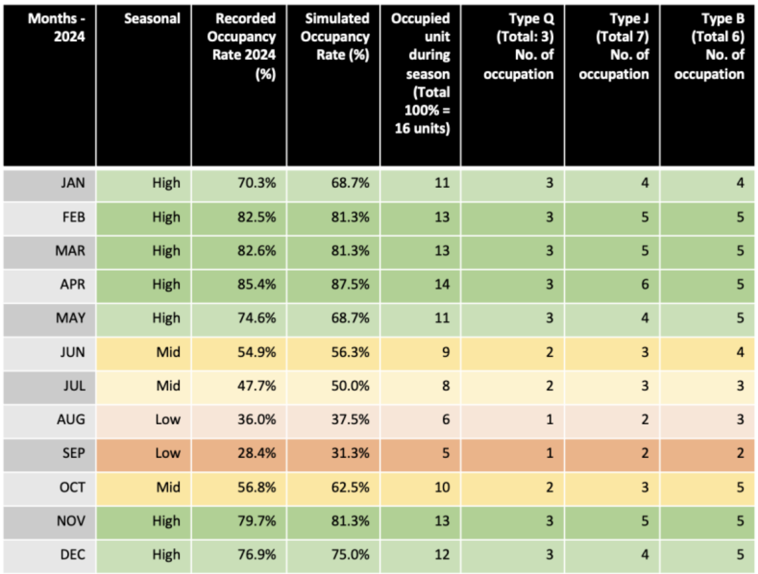
Figure 28. Architecture and building physics of the simulated buildings (Source: EGS-plan (Bangkok) Co., Ltd.)

5.2.3 Occupancy Modelling

Occupancy is a critical driver of energy demand in resort applications. To reflect real-world operation, WP4 explicitly incorporates seasonal occupancy variations observed at Koh Munnork in 2024 (see Figure 9).

Electricity load profiles were generated for each building type and subsequently aggregated using an Excel-based model. Monthly occupancy rates were applied to the bungalow categories (Table 7), resulting in a dynamic annual load curve that captures fluctuations in guest numbers and associated cooling and equipment loads.

Table 7. Actual occupancy vs. simulated occupancy (Source: EGS-plan (Bangkok) Co., Ltd. based on actual occupancy recording by Koh Munnork Private Island)



Months - 2024	Seasonal	Recorded Occupancy Rate 2024 (%)	Simulated Occupancy Rate (%)	Occupied unit during season (Total 100% = 16 units)	Type Q (Total: 3) No. of occupation	Type J (Total 7) No. of occupation	Type B (Total 6) No. of occupation
JAN	High	70.3%	68.7%	11	3	4	4
FEB	High	82.5%	81.3%	13	3	5	5
MAR	High	82.6%	81.3%	13	3	5	5
APR	High	85.4%	87.5%	14	3	6	5
MAY	High	74.6%	68.7%	11	3	4	5
JUN	Mid	54.9%	56.3%	9	2	3	4
JUL	Mid	47.7%	50.0%	8	2	3	3
AUG	Low	36.0%	37.5%	6	1	2	3
SEP	Low	28.4%	31.3%	5	1	2	2
OCT	Mid	56.8%	62.5%	10	2	3	5
NOV	High	79.7%	81.3%	13	3	5	5
DEC	High	76.9%	75.0%	12	3	4	5

This approach ensures that the simulation results are not based on theoretical full-load operation but reflect actual operational behaviour, which is essential for realistic system sizing and economic assessment.

5.2.4 Climatic Conditions in Southeast Asia

A key objective of WP4 was to assess how climatic differences within Southeast Asia influence resort energy demand and renewable energy supply. Indonesia, the Philippines, and Vietnam were selected as representative countries. Due to their coastal location and data availability, Jakarta, Manila, and Ho Chi Minh City were chosen as reference cities. The analysis shows that average ambient temperatures across all locations are very similar, typically ranging between 28 °C and 32 °C throughout the year (Figure 29). As a result, cooling demand remains broadly comparable across all sites.

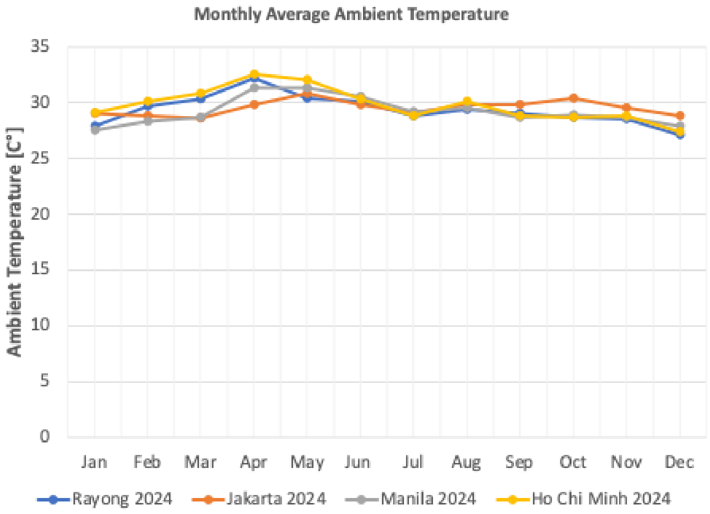


Figure 29. Monthly average ambient temperature in four locations in Southeast Asia in 2024 (Source: EGS-plan (Bangkok) Co., Ltd.)

Differences are more pronounced in solar irradiation patterns, particularly for Jakarta, see Figure 30. This can be explained by its location south of the equator, while Rayong, Manila, and Ho Chi Minh City are located at similar latitudes north of the equator. These findings are important for PV system design but do not fundamentally alter the overall system concept.

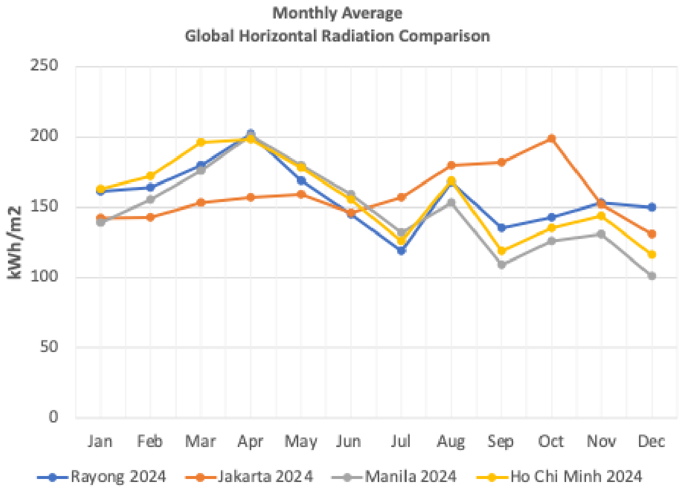


Figure 30. Monthly average solar radiation in four locations in Southeast Asia in 2024 (Source: EGS-plan (Bangkok) Co., Ltd.)

5.2.5 Fuel Price Assumptions

In addition to climatic factors, WP4 considers country-specific diesel fuel prices, as these strongly influence the economic comparison between renewable systems and conventional diesel generation (see Figure 31).

Figure 31. Fuel costs for Diesel in Thailand Indonesia, Philippines and Vietnam (Source: EGS-plan (Bangkok) Co., Ltd. based on average GlobalPetrolPrices (2024))

The analysis shows significant variation across the region:

- The Philippines and Thailand exhibit relatively high diesel prices.
- Indonesia shows moderate fuel prices.
- Vietnam has notably low diesel prices.

5.3 Calibration Process

The calibration process was conducted using the energy modelling software DesignBuilder V7 with weather data of Rayong in 2024 according to ASHRAE Standard 14. ASHRAE Standard 14 describes a procedure to verify that a building energy simulation model accurately represents the real building by statistically comparing simulated energy use with measured data. The model is considered calibrated when key error metrics—such as Normalized Mean Bias Error (NMBE) and Coefficient of Variation of the Root Mean Square Error (CV(RMSE))—fall within the acceptance limits defined by ASHRAE, ensuring the model is reliable for performance analysis and savings evaluation.

The simulation model was created as described in the previous chapter and the simulation results were compared with the measured energy consumption and load curve of 2024. The following parameters are unknown because they underly the influence of the guests (e.g., set temperature of air-conditioning) or are difficult to measure (air infiltration, utilization factor) and were modified to calibrate the simulation model:

- Room set temperature in air-conditioned buildings
- Air infiltration in air-conditioned buildings
- Utilization factors of pumps

The resulting errors of the calibration process are shown in Table 8. The errors are with 0.77% and 6.3% significantly below ASHRAE 14 requirements. Therefore, the simulation was considered be calibrated.

Table 8. Calibration error vs. ASHRAE 14 requirements (Source: EGS-plan (Bangkok) Co., Ltd. based on ASHRAE 14)

		ASHRAE 14 requirements
Normalized Mean Bias Error (NMBE)	0.77%	≤ 5%
Coefficient of Variation of the Root Mean Square Error (CV(RMSE))	6.3%	≤ 15%

Figure 32 shows a comparison of the measured value in 2024 and the results of the calibrated simulation. The energy breakdown shows an excellent agreement with only minor deviation. Annex 8.4 shows a comparison of the load curves and the monthly energy consumption.

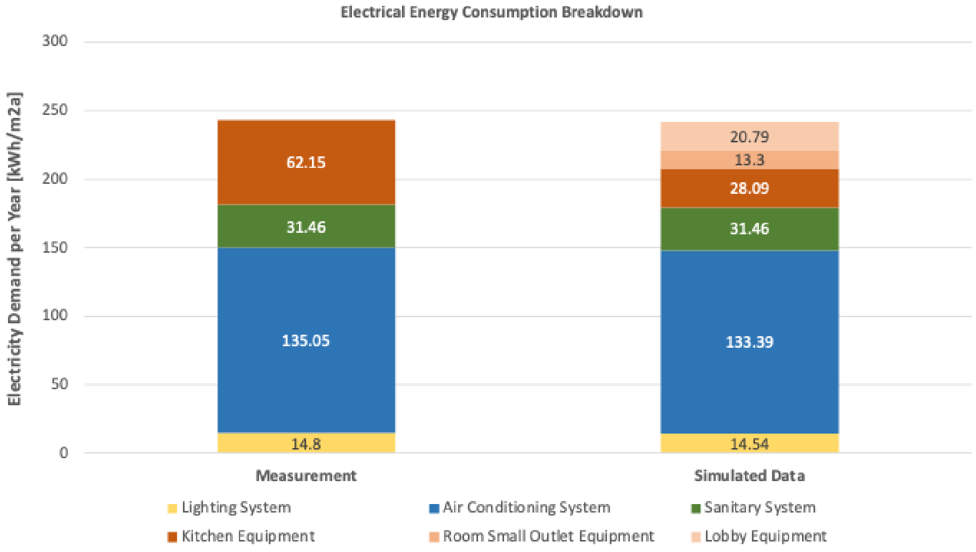


Figure 32. Comparison of the energy breakdown of 2024 and simulation results (Source: EGS-plan (Bangkok) Co., Ltd.)

5.4 Results of the Parameter Study

5.4.1 Energy Demand

Figure 33 shows a comparison of the simulated energy demand of the calibrated model of Koh Munnork resort applying weather data sets for Jakarta, Manila and Ho Chi Minh City.

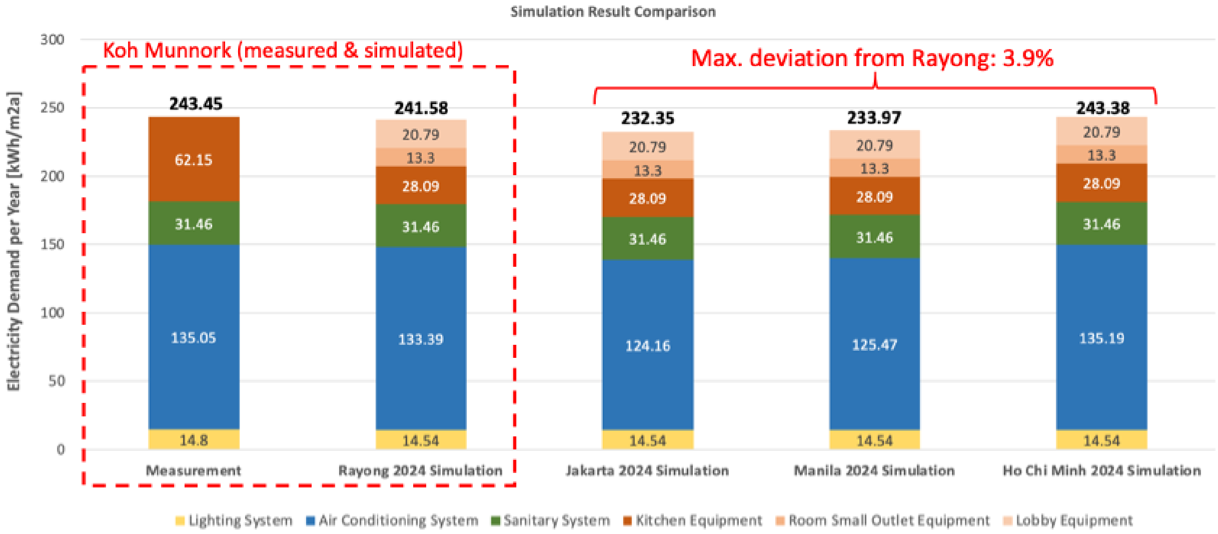


Figure 33. Comparison of the energy demand of the Koh Munnork resort in different SEA locations (Source: EGS-plan (Bangkok) Co., Ltd.)

The first two columns show the measured energy demand data of Koh Munnork in 2024 in comparison to the calibrated simulation model. Next is the simulated energy demand when using the weather data of Jakarta. The energy demand is 3.9% lower. The results for Manila are very similar to the Jakarta 2024 simulation, while Hoh Chi Minh is almost the same as the measured energy consumption in Rayong. In summary, it can be stated that the climate in the different locations in Southeast Asia has with only 3.9% deviation only little influence on the energy demand of the resort.

5.4.2 Re-design of the HESS/BESS system

The energy simulation in the previous chapter showed, that the climate has only a minor impact on the energy demand. However, since the energy self-sufficient supply relies 100% on solar energy, the supply side has also to be considered. Therefore, the electricity load curves which were produced during the demand analyses were imported into the Excel tool and combined with the local solar radiation data in Jakarta, Manila and Ho Chi Minh City.

A parameter study based on the Excel tool was carried out with the goal to minimize the Life-Cycle Costs of the energy supply system without causing critical electricity shortages. The results of the parameter study and the adapted energy supply systems are shown in Table 9. Major deviations from the sizing of the baseline concept (Thailand) are marked in red.

Table 9. Results of the adaptation of the PV/HESS/BESS system design to different locations (Source: EGS-plan (Bangkok) Co., Ltd.)

Component	Rayong	Jakarta	Manila	Ho Chi Minh
PV System [kWp]	425	425	**500**	425
Battery [kWh]	800	**725**	**750**	**700**
Electrolyzer [kW]	4.8	4.8	**9.6**	4.8
H2 Tank [kg]	52.5	51	52.5	52.5
Fuel Cell [kW]	63	67	49	59
Critical Shortage [h/a]	0	0	0	0

In comparison to Thailand, the energy supply in Indonesia requires only a downsizing of the battery storage from 800 to 725 kWh. The system for Manila requires the most modifications: the size of the PV system and electrolyzer must be increased, while the size of the battery can be decreased. Like Jakarta, for the system in Ho Chi Minh City a downsizing of the battery system is sufficient.

In summary, the suggested carbon neutral self-sufficient energy supply system with photovoltaic, battery and H2 storage works for an off-grid resort like Koh Munnork in Southeast Asia with only slight modifications of the size of the main components.

5.4.3 Comparison of Investment Costs

Figure 34 shows a comparison of the investment costs considering the modifications of the energy supply system as shown in Table 9.

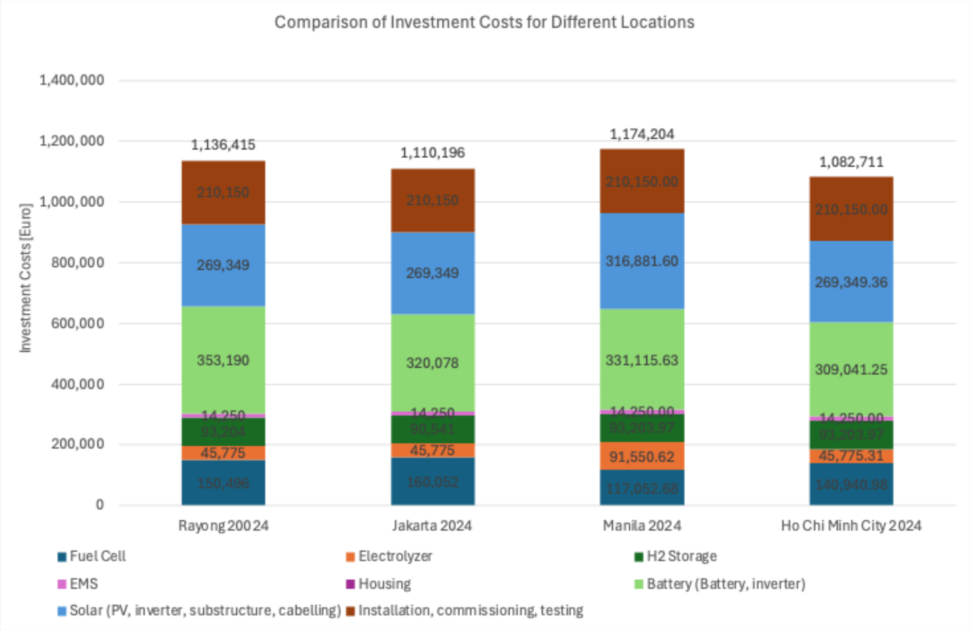


Figure 34. Comparison of required investment costs for the self-sufficient energy supply system (Source: EGS-plan (Bangkok) Co., Ltd.)

Because system modifications are limited, total investment costs remain broadly comparable across all locations. This indicates that transferring the concept to other Southeast Asian countries does not significantly increase upfront capital requirements.

5.4.4 Life-Cycle Costs

Figure 35 shows a comparison of the LCC between Diesel Generator systems and the PV/HESS/BESS systems for different locations in Southeast Asia. The LCC calculation was carried out according to the NPV method and the financial boundary conditions can be found in chapter 4.5.3 apart from the fuel price. The fuel price was adapted to the respective location as stated in chapter 5.2.5.

While the life-cycle costs for the PV/HESS/BESS system in Rayong are significantly lower than the Diesel genset system, the difference in Jakarta is much smaller. The reason for this is the low diesel price in Indonesia. Nonetheless the PV/HESS/BESS system is economically feasible also in Indonesia. In the Philippines with high fuel prices the economic feasibility is even higher than in Thailand and Indonesia. The savings over 20 years sum up to 200,000 Euro. The only country where the PV/HESS/BESS is not economically viable is Vietnam. Even though the investment costs for the PV/HESS/BESS system are the lowest compared to the other countries the system is not economically viable due to the extremely low fuel costs.

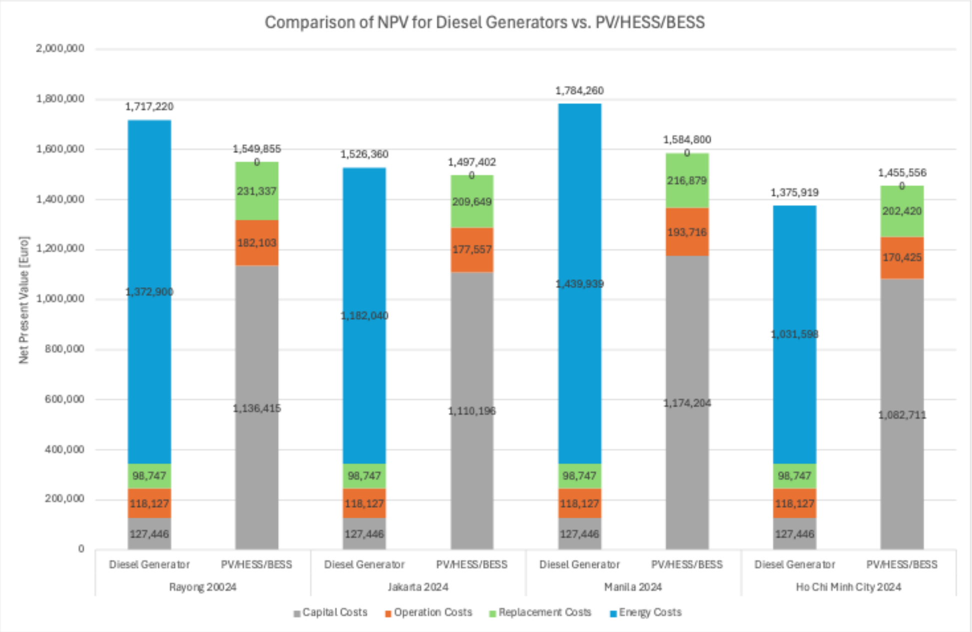


Figure 35. Comparison of Diesel Generator and PV/HESS/BESS systems for different locations (Source: EGS-plan (Bangkok) Co., Ltd.)

5.4.5 Comparison of Levelized Cost of Energy (LCOE)

Figure 36 shows the LCOE for the different locations in Southeast Asia.

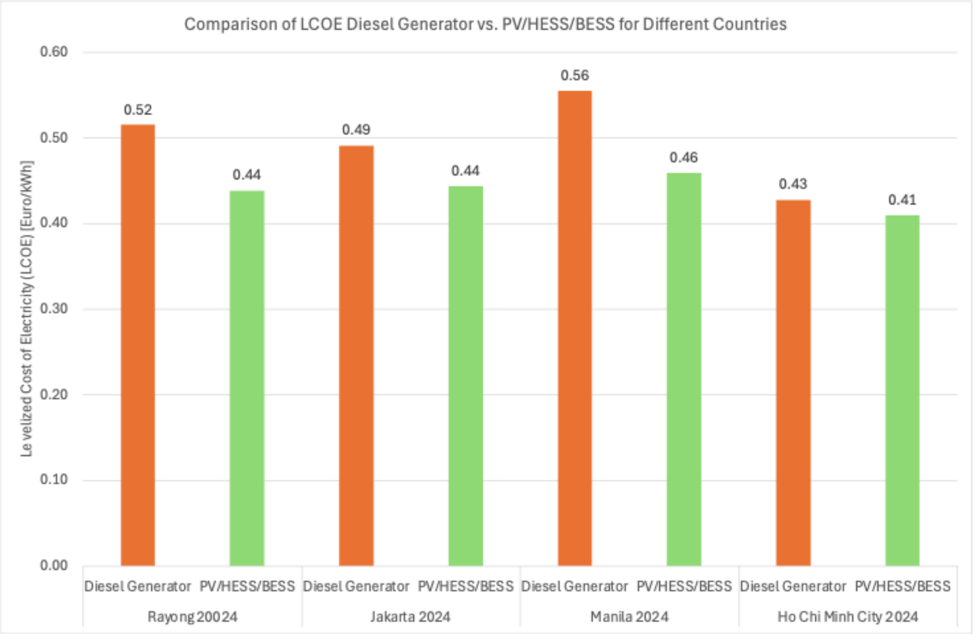


Figure 36. Comparison of Levelized Cost of Energy (LCOE) for different locations (Source: EGS-plan (Bangkok) Co., Ltd.)

The LCOE comparison confirms the life-cycle cost findings. In most assessed locations, the renewable system achieves lower or comparable electricity generation costs, while providing additional benefits such as price stability, reduced fuel price exposure, and zero local emissions.

5.5 Summary and Recommendation

The country comparison shows that the carbon-neutral, energy self-sufficient PV/HESS/BESS system is technically applicable in all assessed locations, as climatic differences have only a minor influence on the overall energy demand and require only moderate adjustments in system sizing. The economic performance, however, differs significantly between the countries and is primarily driven by local diesel prices rather than by investment costs or solar resource.

For Thailand, represented by Koh Munnork Private Resort, the renewable system demonstrates a clear economic advantage over the diesel-based reference. The baseline system configuration can largely be maintained and results in substantially lower life-cycle costs and levelized cost of energy. This confirms Thailand as a highly suitable entry market for the implementation and replication of the concept. Pilot projects in off-grid island resorts and remote hospitality facilities should therefore be prioritized, as they offer both strong economic performance and high visibility for further market development.

In Indonesia, the system remains technically feasible and requires only a slight reduction in battery capacity. The economic advantage compared to diesel generation is smaller than in Thailand due to the comparatively low fuel price. Nevertheless, the renewable system still achieves comparable life-cycle costs while providing additional benefits such as price stability and reduced dependence on fuel logistics. Market implementation in Indonesia should therefore focus on remote island locations where real diesel generation costs are significantly higher than mainland fuel prices, and where energy security plays a major role. In addition, concessional financing and climate-related funding instruments can further improve the business case.

The results for the Philippines show the most favourable economic conditions for the renewable supply system. High diesel prices lead to the largest life-cycle cost savings despite the need for an increased PV capacity and a larger electrolyzer. This makes the Philippines the most promising country for near-term deployment from an economic perspective. The concept is particularly suitable for off-grid island resorts and remote tourism infrastructure, where it can serve as a cost-reduction measure while simultaneously supporting decarbonization targets. Early demonstration projects in this market are recommended in order to enable rapid scaling.

In Vietnam, the technical feasibility of the system is confirmed, and the required investment costs are even slightly lower than in the other countries. However, the very low diesel price results in higher life-cycle costs for the renewable system compared to the conventional solution. Under the current market conditions, purely economic implementation is therefore not expected. Activities in Vietnam should focus on applications with additional drivers, such as corporate decarbonization strategies, energy autonomy, or limited grid availability, and should be supported by international climate finance or pilot project funding. A reassessment of the economic viability is recommended in the event of rising fuel prices or the introduction of carbon pricing mechanisms.

Overall, the analysis confirms that the developed system concept is transferable throughout Southeast Asia and that its economic attractiveness is mainly determined by local fuel costs. Countries and regions with high diesel prices, high transport costs for fuel, or strong decarbonization ambitions offer the most favourable conditions for implementation. Thailand and the Philippines are therefore identified as priority markets for initial deployment, while Indonesia represents a medium-term opportunity with a focus on remote locations. Vietnam is currently more suitable for demonstration projects and strategic market preparation than for purely cost-driven investments.

6 Work Package 5: Dissemination of Project Results

Dissemination of project results was a key component of the Koh Munnork project, aiming to raise awareness of carbon-neutral, energy self-sufficient solutions for off-grid resorts and islands and to promote knowledge exchange among stakeholders from the hospitality sector, technology providers, financial institutions, and public authorities. The project findings were presented at three major events at national and regional level, each addressing different target audiences and dissemination objectives.

6.1 PHIST 2025 – Phuket Hotels for Islands Sustaining Tourism (September 2025)

The project results were disseminated to a broad hospitality and tourism audience at PHIST 2025, organized by the Phuket Hotels Association. The event brought together hotel owners, resort operators, engineers, and sustainability practitioners with a strong focus on low-carbon tourism and island sustainability.

During a dedicated presentation, the Koh Munnork project was introduced as a practical example of how off-grid resorts can transition away from diesel generation by combining photovoltaic systems, battery storage, and green hydrogen technologies. The presentation highlighted the project's technical concept, its relevance for island contexts, and its potential contribution to long-term cost stability and emissions reduction in the hospitality sector.

In addition, the project was showcased at the EGS-plan exhibition booth, where participants engaged in in-depth discussions on the feasibility, operational aspects, and scalability of green hydrogen solutions. This setting allowed for direct interaction with potential adopters, helping to translate technical findings into practical considerations for hotel and resort operators. The event therefore played a key role in raising market awareness and demonstrating the applicability of the Koh Munnork approach to similar island destinations.

6.2 H2Uppp Southeast Asia Conference on Green Hydrogen and Power-to-X (July 2025, Bangkok)

The Koh Munnork project was further disseminated at the H2Uppp Southeast Asia Conference on Green Hydrogen and Power-to-X, organized by GIZ in cooperation with the German Thai Chamber of Commerce (GTCC). This event primarily addressed policy makers, technology providers, financiers, and the international development community.

Within a panel discussion, the project was presented as a bankable pilot case demonstrating how green hydrogen can be integrated into decentralized energy systems for remote locations. The presentation focused on the feasibility study results, including system design, economic performance, and the role of hybrid PV-battery-hydrogen configurations in replacing diesel generators.

The conference provided a platform to position the Koh Munnork project within a broader regional context, highlighting its relevance for public-private partnerships, regulatory frameworks, and financing mechanisms. The discussion emphasized that pilot projects such as Koh Munnork are essential to reduce perceived risks, build local experience, and support the scale-up of green hydrogen applications in Southeast Asia.

6.3 H2Uppp Indonesia Event (November 2025, Jakarta)

A further dissemination activity took place at an H2Uppp event in Indonesia, targeting stakeholders from government institutions, industry, and the energy sector. At this event, the Koh Munnork project was presented as a transferable pilot for off-grid hotels and resorts in Southeast Asia, with relevance for Indonesia's many remote islands.

The presentation focused on the technical and economic findings of the feasibility study, including the comparison between diesel-based generation and renewable hybrid systems with hydrogen storage. Special attention was given to the economic modelling results, which demonstrate competitive levelized cost of energy under certain boundary conditions, as well as the significant environmental benefits.

The event also served as a platform to discuss next steps for scaling up similar solutions, including financing needs and potential replication pathways. By sharing the Koh Munnork experience with Indonesian stakeholders, the project contributed to regional knowledge exchange and strengthened awareness of green hydrogen as a viable option for decarbonizing remote energy systems.

7 Overall Conclusion and Outlook

The “Green Hydrogen for Energy Self-Sufficient Hotels, Resorts and Islands” project demonstrates that green hydrogen-based hybrid energy systems consisting of photovoltaic generation, battery storage and hydrogen energy storage represent a technically robust and replicable solution for the decarbonisation of off-grid islands and resorts in Southeast Asia. The feasibility study carried out for the pilot site Koh Munnork Private Island confirms that a renewable energy system with hydrogen as long-term storage can reliably supply the resort with electricity throughout the year while eliminating local emissions, reducing environmental risks related to diesel transport and handling, and significantly improving acoustic conditions for staff and guests.

From a technical perspective, the analysis shows that the combination of PV and battery storage alone is not sufficient to guarantee full energy self-sufficiency under the given load profile and seasonal solar variations. The hydrogen system fulfils the essential function of long-term and seasonal storage and ensures system reliability during extended periods of low solar radiation. The study further confirms that commercially available PEM fuel cells and AEM electrolyzers are suitable for this application in terms of scalability, operational flexibility and maintenance requirements. Containerised system design and adapted transport logistics enable implementation even under the challenging boundary conditions of remote islands without port infrastructure. The technical concept is therefore considered mature and transferable to similar sites across Southeast Asia.

The economic assessment shows that, despite significantly higher upfront investment costs compared to diesel generators, the optimised PV/HESS/BESS configuration achieves lower life-cycle costs and a lower levelized cost of energy for the Koh Munnork case. The main economic driver is the avoidance of diesel fuel consumption and the associated logistics. The parameter study for other Southeast Asian countries confirms that the economic viability of the concept is determined primarily by local diesel prices rather than by climatic conditions or investment costs. High fuel price environments such as the Philippines offer particularly favourable conditions, while low fuel price markets such as Vietnam currently limit purely cost-driven implementation.

The central barrier identified in the project is not technical feasibility but financing. The high upfront capital expenditure for renewable and hydrogen systems contrasts with the low initial investment required for diesel generators. Access to commercial loans is constrained by relatively high interest rates and collateral requirements, which cannot be fulfilled in the case of Koh Munnork due to the lack of land ownership. As a result, conventional project financing is unlikely under current conditions. Soft loans, grant programmes and blended finance approaches therefore play a key role in enabling implementation. In addition, regulatory procedures involve multiple authorities and require early coordination, although no fundamental regulatory obstacles to project realisation were identified.

The findings of the project have several important implications for the regional scale-up of hydrogen-based off-grid energy systems. First, the concept is technically transferable and can be standardised through modular system design. Second, economic feasibility is strongest in remote locations with high real diesel generation costs, difficult fuel logistics or strong decarbonisation targets. Third, suitable financing structures are a prerequisite for market deployment and are more decisive than further technological optimisation at the current stage of development.

Based on these results, the following next steps are recommended. As a priority, a real pilot implementation at Koh Munnork or a comparable site should be prepared in order to move from feasibility to execution and to generate operational data under real conditions. In parallel, financing concepts based on public development banks, international climate finance and innovative ownership models such as energy-as-a-service should be developed to overcome the upfront investment barrier. Further activities should focus on the standardisation of technical system layouts, the development of simplified permitting roadmaps in cooperation with national authorities, and the identification of priority markets with high fuel costs and suitable framework conditions, in particular island regions in Thailand and the Philippines.

In conclusion, the project provides clear evidence that green hydrogen can play a key role in enabling carbon-neutral, energy self-sufficient islands and resorts in Southeast Asia. While technological solutions are already available, the successful realisation of projects will depend on appropriate financing mechanisms, supportive policy frameworks and the implementation of lighthouse projects that demonstrate the technical and economic performance under real operating conditions.

8 Annex

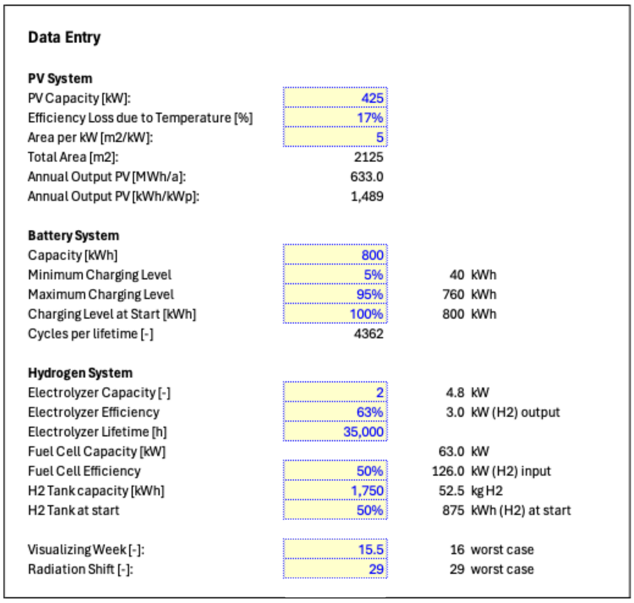
8.1 Annex 1: Turnkey Provider for Green Hydrogen systems

Table 10. Green hydrogen installer with focus on energy self-sufficiency projects in Southeast Asia and Thailand [source: EGS-plan (Bangkok) Co., Ltd.].

	PT MBR Global Indonesia	**Somboon Co., Ltd. (H2 Powercell)**	**Bender-IS Co., Ltd.**	**Chavin Co., Ltd.**
Company type	System Integrator	EPC	EPC	System Integrator
Preferred Electrolyzer	Enapter (certified partner Malaysia, Indosia, Singapore)	Enapter H2 Powercell	Enapter	Enapter (certified partner for Thailand)
Preferred Fuel Cell	Horizon / H2 CoreSystems	H2 Powercell	SFC Energy	Intelligent Energy (UK)
Example projects in Thailand / SEA	Phi Suea House, Malaysia, Indonesia, Philippines	Koh Jik / Thailand	EGAT / Bangkok	DAD / Bangkok
Location	Indonesia	Thailand	Thailand	Thailand

8.2 Annex 2: Technical and Financial Assumptions of the Excel PV/HESS/BESS Sizing Tool [source: EGS-plan (Bangkok) Co., Ltd.]

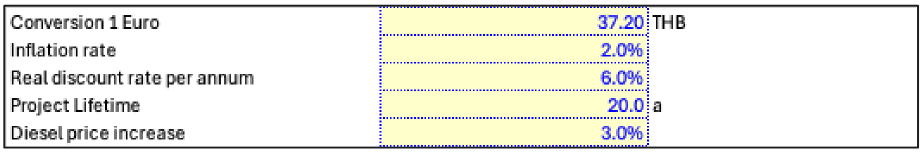
Technical Assumptions:



Data Entry

PV System			
PV Capacity [kW]:	425		
Efficiency Loss due to Temperature [%]	17%		
Area per kW [m2/kW]:	5		
Total Area [m2]:	2125		
Annual Output PV [MWh/a]:	633.0		
Annual Output PV [kWh/kWp]:	1,489		
Battery System			
Capacity [kWh]	800		
Minimum Charging Level	5%	40	kWh
Maximum Charging Level	95%	760	kWh
Charging Level at Start [kWh]	100%	800	kWh
Cycles per lifetime [-]	4362		
Hydrogen System			
Electrolyzer Capacity [-]	2	4.8	kW
Electrolyzer Efficiency	63%	3.0	kW (H2) output
Electrolyzer Lifetime [h]	35,000		
Fuel Cell Capacity [kW]		63.0	kW
Fuel Cell Efficiency	50%	126.0	kW (H2) input
H2 Tank capacity [kWh]	1,750	52.5	kg H2
H2 Tank at start	50%	875	kWh (H2) at start
Visualizing Week [-]:	15.5	16	worst case
Radiation Shift [-]:	29	29	worst case

Financial Assumptions:



Conversion 1 Euro	37.20	THB
Inflation rate	2.0%	
Real discount rate per annum	6.0%	
Project Lifetime	20.0	a
Diesel price increase	3.0%	

Calculation of Levelized Cost of Energy (LCOE)

$$\mathrm{CRF} = \frac{r(1+r)^N}{(1+r)^N-1}$$

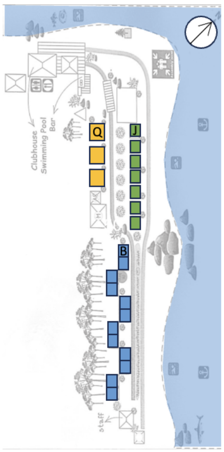
CRF: Capital Recovery Factor
r: discount rate
N: lifetime of the systems

$$LCOE = \frac{CAPEX \cdot CRF + OPEX_{fixed}}{E_{annual}} + OPEX_{variable}$$

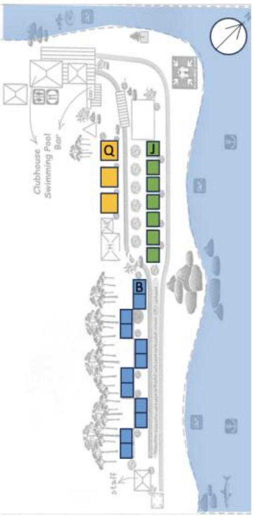
LCOE: Levelized Cost of Energy
CAPEX: Capital Expenditure
CRF: Capital Recovery Factor
OPEX: Operational Expenditure
E_{annual}: Annual Energy Generation

8.3 Annex 2: Building Types and Electric Load [source: EGS-plan (Bangkok) Co., Ltd.]

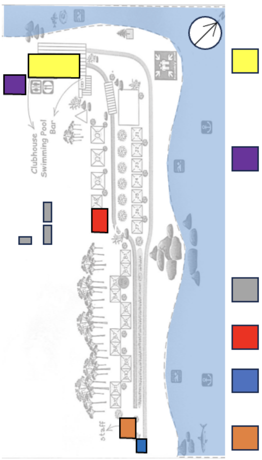
Bungalow Type Summary



Type	Name	No of unit	Unit area(m2)	Max Occupancy	Uses of electricity	Lighting Power Density (W/m2)*	Electrical outlet Power Density (W/m2)	Heat gain and infiltration Schedule
Type Q 	Garden Cottage	3	40.7	2	• Air-conditioning • Lighting • Small electrical device outlet	2.61	3.15 (DesignBuilder)	**Occupancy& Electrical outlet schedule** 14:00 – 09:00 **Lighting schedule** 16:00 – 22:00 **Infiltration *(Calibrated data)*** 2.75 ach 24/7
Type J 	Beach front	7	34.0	2	• Air-conditioning • Lighting • Small electrical device outlet	2.34	3.15 (DesignBuilder)	
Type B 	Beach view	6 (12 rooms)	56.0	2 per room	• Air-conditioning • Lighting • Small electrical device outlet	1.41	3.15 (DesignBuilder)	

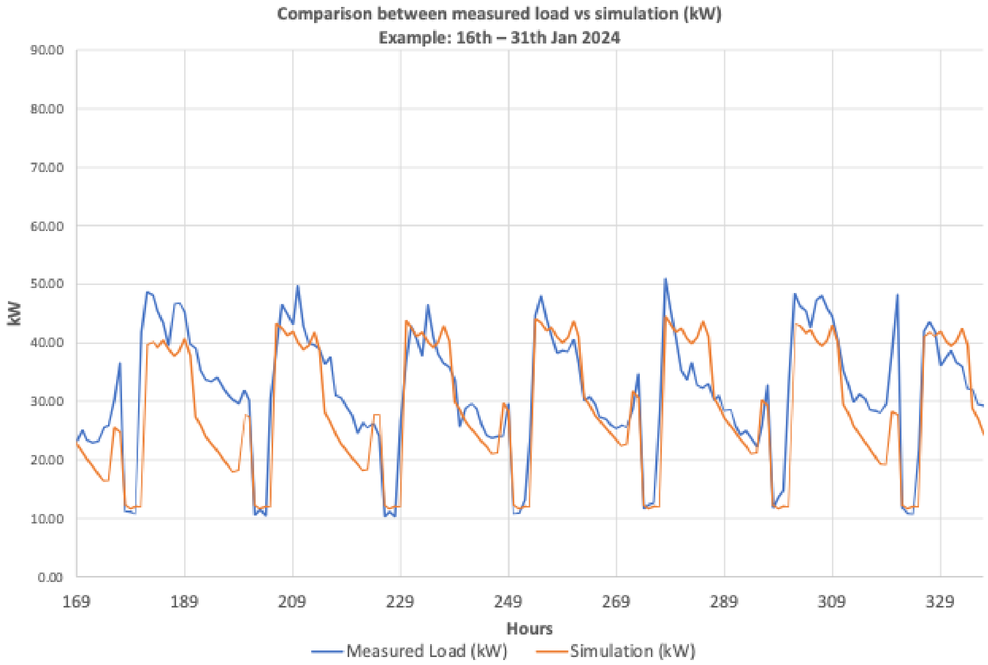


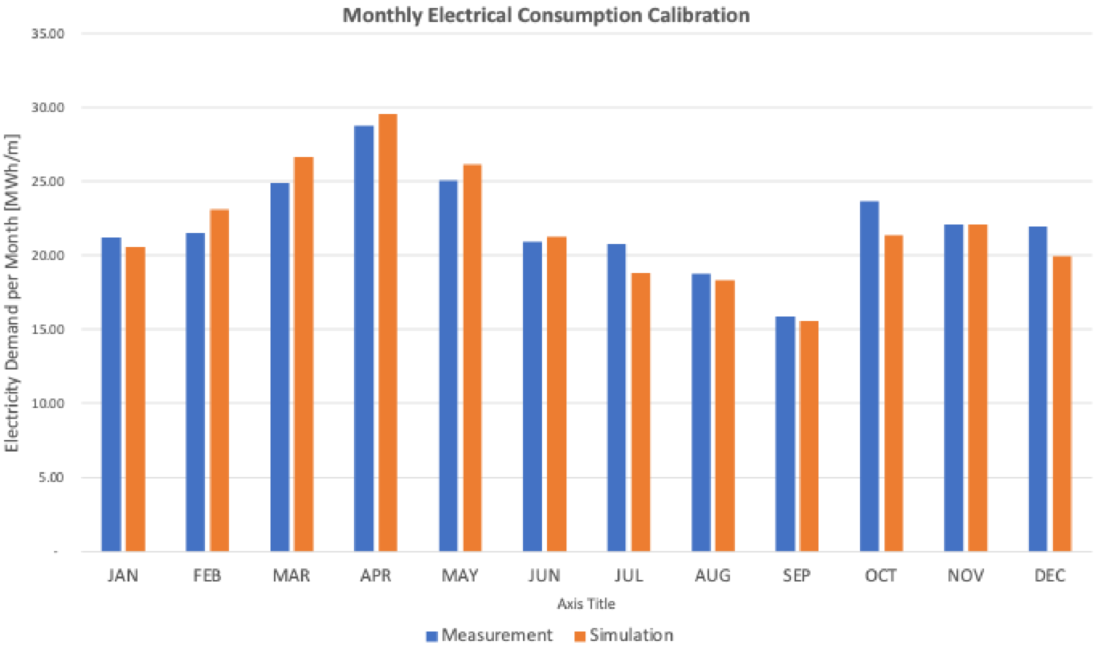
Type	Picture	Name	Cooling System Type	Average CoP*	Tset	HVAC Schedule
Type Q 		Garden Cottage	Spilt type	3.6	22°C *Calibrated data (Operative Temp during occupied hours = ~ 24-25°C)*	13:00 – 09:00
Type J 		Beach front	Spilt type	3.6		
Type B 		Beach view	Spilt type	3.4		



Area	Air-condition (Y/N)	No. of staff	Uses of electricity	Lighting Electrical Consumption per day (kWh/day)*	Equipment Electrical Consumption per day (kWh/day)*
Reception and dining area	N	30	• Lighting • Water coolers • Fridges • Coffee machine • Water heater • Ceiling fans	52.87	72.26
Kitchen	N		• Lighting • Ice machine • Fridges • Water coolers • Washing machines • Exhaust fans • Wall fans • Ceiling fan		109.99
Staff Dormitory (Cluster)	N		• Air conditioning • Lighting		3.15 W/m2 Small Electrical Outlet (DesignBuilder)
Staff Dormitory (Beach front)	Y		• Lighting • Fans		
Staff House (End of beach)	Y		• Lighting • Fans • Air conditioning		
Owner house	Y	1	• Lighting • Fans • Air conditioning		
Pump and Sanitary system (Not appeared in layout)	-	-	• Fresh water pumps • Booster pumps • Pool pump • Instantaneous water heater	-	92.25

8.4 Annex 3: Comparison of Measurement and Results of the Calibrated Simulation Model [source: EGS-plan (Bangkok) Co., Ltd.]





The International Hydrogen Ramp-up Program (H2Uppp) is supporting entrepreneurial engagement in the ramp-up of hydrogen in the Global South and is a funding program of the:

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Implementation by:

giz Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH